

A Study on the Possibility of Using Greywater in Irrigation of Agricultural Products

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Resumo

O declínio da pluviosidade anual, juntamente com o aumento da procura de água para fins agrícolas originou uma nova crise no mundo actual. Neste aspecto, atenções renovadas estão viradas para a descoberta de novos recursos hídricos, como efluentes líquidos, devido à sua diminuição consecutiva nas últimas décadas. Embora tenha havido um desenvolvimento de novas metodologias e infra-estruturas de tratamentos de águas residuais, estes não foram largamente aplicados em produtos de irrigação agrícola. Adicionalmente, estudos recentes têm demonstrado que alguns produtos agrícolas têm um risco acrescido de ser contaminados, não podendo ser tratados por infra-estruturas de baixo custo.

Olhando para situações do quotidiano, foi demonstrado que a maior parte dos efluentes produzidos podem estar contidos numa categoria de menor poluição, chamada Água Cinzenta. Se se excluir a categoria chamada Água Preta, que inclui dejetos humanos, essencialmente provenientes de sanitas, a maior parte dos efluentes de uma casa é produzida a partir de cozinhas, banheiras, máquina de lavar louça, lavatórios ou mesmo máquina de lavar roupa, sendo este conjunto denominado Água Cinzenta. Uma vez que a Água Cinzenta contém menos poluição bacteriana, pode ser considerada um efluente com uma boa relação custo-eficiência para ser tratada e reutilizada.

Nesta dissertação, foram estudadas metodologias actuais para tratamento de Água Cinzenta, juntamente com a avaliação de efeitos de irrigação de produtos agrícolas com e sem o tratamento da Água Cinzenta. São ainda apresentados argumentos que recomendam a irrigação de colheitas com Água Cinzenta.

Abstract

The decrease in the annual rainfall, alongside with the increase of water demand in agricultural fields, originated a new crisis in today's world. In this regard, attentions are directed towards finding new rater resources,like liquid effluents, for these have been steadily declining in the last decades. Although there have been some developments in wastewater treatment methodologies and facilities, they have not been widely applied for irrigating agricultural fields. Besides, recent studies have shown that some agricultural products present an added risk of being contaminated, preventing them from being treated with low-cost facilities.

Having a look to normal daily life, it has been shown that the largest part of the effluents produced can be categorized in a less polluted category, called Greywater. If the so called Black Waters, which include human dejects coming from toilets, are excluded, most of the effluents from a household are produced in bathtubs, dishwater, lavatories, or even washing machines, being denominated Greywater. Since greywater contains much less microbial pollution, it can be considered as a cost-effective effluent to be treated and reused.

In this dissertation, current methodologies for treating greywater were addressed, together with the evaluation of the effects of irrigating agricultural products with treated and untreated greywater. Further discussion provides arguments for recommending irrigating crops with greywater.

To My Sweetheart
Who Rules My Dreams . . .

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The activist is not the man who says the river is dirty.
The activist is the man who cleans up the river.
- Ross Perot

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Chapter 1

Introduction

Nowadays, the water crisis is an upcoming phenomenon that threatens countries all over the world. It is estimated that water scarcity affects a fifth of world's population. The coincidence of the increase in the world population and the decrease in annual rainfall, has complicated the situation. Therefore, it is estimated that more persons will be influenced by the freshwater shortage [Teh et al., 2015] [Matos et al., 2014].

Various parts of world are suffering from a shortage of water resources. Regions such as the Middle East, Australia, and southwest of United States are possible regions confronting drought. Water shortage can be even happening in non-arid areas. Regions such as Japan are being affected due to a high demand of freshwater. The development of countries and the increasing demands of the population, on one side, and the shortage of freshwater on the other side, have caused an increase in the demand of energy to provide freshwater for, not only potable uses, but also irrigation and urban usages, hence making water usage and energy demands tightly linked to each other. Therefore, the increase in water provision will increase the amount of green gases emitted to the atmosphere [Matos et al., 2014].

A study of the daily life of a typical citizen, in urban areas of developed countries, shows that the water consumption can vary from $15 - 55L$ up to $90 - 120L$ per day [Nolde, 2000]. Providing such amounts of water from first-hand resources requires, not only a great effort, but also a lot of energy, which can emit a lot of carbon dioxide (CO_2). Thus, the problem of providing freshwater is not only a sustainable, but also an energy efficient issue. A study carried out by Rothousen and Conway [Rothausen and Conway, 2011] revealed that the greenhouse-gases emitted by typical water treatment facilities have been underestimated in planning and management procedures.

The cause of water shortage should not be sought only in population growth. Reasons such as the mismanagement of water resources, increase in urbanization, and climate change have also negative effects on current freshwater resources. To fight the water shortage problem, possible prescribed remedies include water conservation and water reuse. Water conservation includes, for instance, the implementation of some regulations which can prevent the usage of freshwater in non-potable uses; for example, rules that restrict house holders to avoid using freshwater for gardening, or and toilet flushing.

Food and Agriculture Organization [Food and Agriculture Organization, 2008] have reported that more than 70% of freshwater consumption is used in agricultural irrigation, worldwide. At the same time, many households in poor areas (including both urban and rural areas) have a limited access to freshwater. There are some alternatives that can be used instead. For instance, wastewater treatment and reuse at the individual household can be considered as a local solution to the emerging problems of supplying water and nutrients needed for household food production. To be more precise, the discussed solution has already been used by farmers worldwide since it is estimated that 10% of the world's population consumes foods which are irrigated with wastewater [World Health Organization, 2006]. Therefore, treatment of wastewater and reusing it for irrigation may supply the increasing demand on freshwater and improve the food production capacity of farms. However, there are significant concerns about the safety of reusing wastewater in irrigation. The main concern is the potential for damaging effects of poor-quality water on soil, plants and finally human's health. Studies have shown that the microbial population of untreated wastewater is very diverse. Microorganisms that can cause illness or disease (which are known as pathogens,) are usually associated with human or animal fecal matter present in wastewater. Diseases such as food-borne illness are thought to be have direct relation with the irrigation with water contaminated with pathogens [Finley et al., 2008].

1.1 An Alternative Water Resource

Source separation of wastewater flows from domestic sources has recently become an important strategy to simplify wastewater treatment. This model is based on excluding human solid wastes (black water) from the remaining wastewater flow (greywater).

Greywater has come to designate wastewater derived from hand basins, showers, baths, laundry machines, and occasionally dishwashers and kitchen sinks. Installing dual reticulation plumbing can be a fast solution to separate the blackwater flow from greywater effluent from the source. The separated greywater can then be routed to an on-site treatment system or sent to a communal greywater facility and reused for other purposes [Diaper and Sharma, 2007]. Greywater recycling not only reduces water requirements of a building, but can also significantly reduce the volume of effluents being sent to the sewer or septic system. Therefore, it is economic and vital, especially for residents of water-scarce regions [Finley, 2008].

1.2 Greywater

Greywater is defined as water collected from sewage discharge of cloth washers, bathtubs, showers and sinks, and does not include wastewater from kitchen, dishwasher and toilet [Al-Jayyousi, 2003]. However, in some studies, sewage originated from dishwashers and kitchen is also considered as greywater. In some references, such as [Madungwe and Sakuringwa, 2007], greywater is defined as the non-toilet wastewater, collected from house activities: showers, baths, hand basins, washing machines and kitchen sinks.

The use of untreated domestic greywater for plants irrigation in small home gardens has several advantages [Holtzhausen, 2005] [Al-Zubi and Al-Mohamadi, 2008]. The most highlighted one can be called potable freshwater saving. Studies have shown that it can reduce household potable water usage by about 30% [Jeppesen, 1996] [Mzini, 2013].

1.2.1 Composition of Greywater

Greywater represents $50-80\%$ of the wastewater from a household. The largest section which produces greywater in any household is the bathroom [Ng, 2004]. Different types of greywater produced in a typical household are shown in Figure 1.1 while it has been explained in Table 1.1.

Greywater usually does not have any unpleasant odor. Comparing to wastewater, greywater is produced in higher temperature. Additionally, it contains readily degradable pollutants, thus it is required to be treated immediately. Storing it in tanks, even for short times, leads to the development of oxygen deficient bacteria and scum will

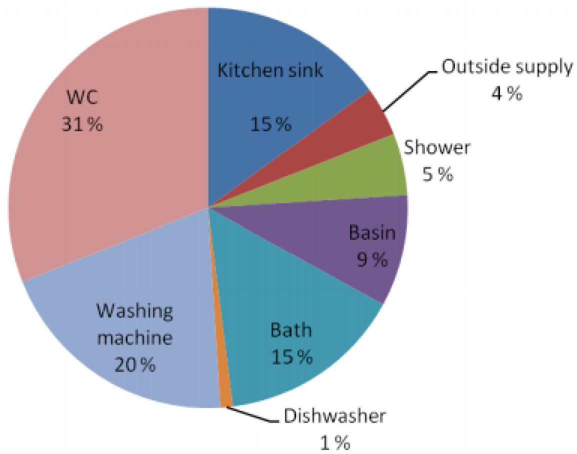

Figure 1.1: Components of domestic greywater [Ng, 2004]

Table 1.1: Different greywater sources (Table is adopted from [Ng, 2004])

Kitchen	Kitchen greywater contains food residues, high amounts of oil and fat, including dishwashing detergents. In addition, it occasionally contains drain cleaners and bleach. Kitchen greywater is high in nutrients and suspended solids. Dishwasher greywater may be very alkaline (due to builders), show high suspended solids and salt concentrations.
Bathroom	Bathroom greywater is regarded as the least contaminated greywater source within a household. It contains soaps, shampoos, toothpaste, and other body care products. Bathroom greywater also contains shaving waste, skin, hair, body-fats, lint, and traces of urine and feces. Grey water originating from shower and bath may also be contaminated with pathogenic microorganisms.
Laundry	Laundry greywater contains high concentrations of chemicals from soap powders (such as sodium, phosphorous, surfactants, and nitrogen) as well as bleaches, suspended solids and possibly oils, paints, solvents, and non-biodegradable fibers from clothing. Laundry greywater can contain high amounts of pathogens when nappies are washed.

be formed which will float on the water in the collection tank [Lehr and Keeley, 2005].

In developed countries, greywater corresponds to about $60-70\%$ of domestic wastewater volume [Friedler, 2004]. Typically, when evaluating basic water quality parameters (total suspended solids or TSS, biochemical oxygen demand or BOD, chemical oxygen demand or COD, turbidity), greywater is ranked to be comparable to a low or medium grade wastewater; however, several properties of greywater need to be considered in order to limit the reuse challenges. Jefferson et al. ([Jefferson et al., 2004]) found that, though similar in organic content to full domestic wastewater, greywater contains fewer solids and has less turbidity than wastewater. The same study also suggested that the COD-BOD ratio in greywater can approach $4:1$, much higher than that of untreated domestic wastewater, which is typically around $2:1$. Since greywater is mainly collected from washing activities, it is richer in surfactants, which in one study reached up to $60mg/L$ [Gross et al., 2005]. As soaps and detergents are often alkaline, the pH of greywater is measured in the range of $7-8$ [Jefferson et al., 2004]. Also, it can contain high concentrations of nitrogen (N), phosphorus (P), and potassium (K). Nutrients minor quantities can be detected in greywater samples, rarely exceeding $5mg/L$ [Surendran and Wheatley, 1998] [Jefferson et al., 2004].

Microbiology evaluations show that both greywater and blackwater can be quite similar, containing analogous species of microorganisms [Ottosson, 2005]. Such levels of organisms used to signal pathogenicity, including fecal coliforms, enterococci, and bacteriophages, consent researchers to rank greywater only mildly less [Jefferson et al., 2004] [Casanova et al., 2001], and in one study even more [Brandes, 1978], contaminated than full blackwater.

Greywater composition varies widely from one household to another, depending on both the personal habits of residents, and the products used in the household. For example, low phosphate concentrations are detected in the greywater collected from a household in which the inhabitants tend to use phosphate-free laundry detergents. Family makeup also impresses the quality and contents of greywater. Other studies have found higher counts of total and fecal coliforms in greywater collected from households with small children [J. B. Rose, 1991] [Casanova et al., 2001]. Greywater characteristics from previous studies are presented in Table 1.2.

Greywater characteristics also vary according to source: each fixture contributing to the greywater collection system will carry its own particular contaminant load. Friedler [Friedler, 2004] recommends excluding fixtures like the kitchen sink and dishwasher from a greywater system, because they constitute only $25-30\%$ of greywater volume

Table 1.2: Greywater characteristics from various characterization studies (*NT= Not tested; *cfu= Colony Forming Unit) [Finley et al., 2008]

Parameter	**[Christova-Boal et al., 1996]**	**[Friedler, 2004]**	**[Surendran and Wheatley, 1998]**
	Bathroom and Laundry	**Shower and Laundry**	**Shower and Laundry**
pH	$6.4 - 10$	$7.4 - 7.5$	$7.6 - 8.1$
TS mg/L	NT	$1090 - 2021$	$631 - 658$
COD mg/L	NT	$319 - 996$	$424 - 725$
$NH_4{}^+ - N$ (mg/l)	$< 0.1 - 15$	$1.2 - 4.9$	$1.56 - 10.7$
P (mg/L)	$0.062 - 42$	$3.3 - 55.0$	$1.63 - 101$
AL mg/L	$< 1.0 - 21$	NT	NT
Ca mg/L	$3.5 - 12$	NT	NT
Cd mg/L	< 0.001	NT	< 0.001
Cu mg/L	$< 0.05 - 0.27$	NT	$0.11 - 0.32$
Mg mg/L	$1.1 - 2.9$	NT	NT
Na mg/L	$7.4 - 480$	$151 - 530$	NT
Pb mg/L	NT	NT	$0.003 - 0.03$
S mg/L	$1.2 - 40$	NT	NT
Fe mg/L	$0.29 - 1.1$	NT	NT
Zn mg/L	$0.09 - 6.3$	NT	$0.059 - 0.31$
Fecal coliform (*cfu/100mL*)	$110 - 3.3 \times 10^3$	4.0×10^6	$600 - 728$
Fecal streptococci (*cfu/100mL*)	$23 - 2.4 \times 10^3$	NT	NT

but contribute nearly half of its COD content. Therefore, a lower effort would be needed to treat less contaminated greywater for further reuse [Finley, 2008].

1.3 Greywater Usage Around the World

1.3.1 United States

During the severe water shortages in states such as California, Southern Arizona, and Florida, in the late 70s, water authorities carried out some researches to implement alternative water sources. The water authorities of the western states suggested the use greywater for irrigation purposes. In 1989 the County of Santa Barbara regulated new rules in order to reuse greywater [Jeppesen and Solley, 1994]. In the next three years, more than 10 cities used the same regulation to provide a new water source. Later, in 1998, 22 western states of the USA adopted rules to use untreated domestic greywater directly for sub-surface irrigation [Emmerson, 1998]. Also, different greywater reuse systems are operating across the United States, mostly for irrigation purposes [Lindstrom, 2000].

1.3.2 Japan

A shortage of potable water in Japan made the Japanese review their water consumption habits. They separated potable and non-potable usage of water by reusing treated wastewater effluent for toilet flushing, ornamental ponds and fountains, and landscape irrigation. This water generally comes from local domestic wastewater treatment plants, that are mostly small scale systems [Thomas et al., 1997] [Jeppesen and Solley, 1994] [Emmerson, 1998]. Restrict guidelines have been enforced to improve the quality of treated effluent; however, the user should take the responsibility for usage circumstances. Greywater is mostly originated from washing purposes like hand-basin toilet, bath water or washing clothes [Thomas et al., 1997].

1.3.3 New Zealand

Households are encouraged, mostly by local councils, to install biological treatment units to reuse household sewage for garden irrigation. It is suggested to use Aerated Wastewater Treatment Systems instead of a traditional septic tank, to improve the quality of treated effluent. The most common application of treated greywater is garden irrigation. There are some regulations recommending the owners to maintain their systems every three years [Ng, 2004].

1.4 Greywater Reuse

Studying water usage in houses shows that the water provided with drinking quality, is used in non-related purposes such as toilet flushing, gardening or car washing, which do not require water with such quality.

The average volume of water being used by households differs not only among developing and developed countries, but also within different regions inside a country. Household water demand, in developed countries, is about 100 to 150L per capita in each day.

Greywater reuse for household can lead to $29-47\%$ reduction in freshwater treatment to produce potable, and it can be reused for many purposes, such as flushing, gardening and washing the floors.

Although treated greywater can be used for potable uses theoretically, unfortunately current practical treatment systems are too sophisticated and involve many units and process equipment. Regarding in-site and decentralized treatment systems, there is a need to develop a system that can be easily implemented and used.

1.4.1 Health Risks Associated with Agriculture Irrigation Using Greywater

Health hazards associated with greywater may arise from several sources as they are reported below:

1. Contamination by pathogenic micro-organisms that includes bacteria, protozoa, viruses and other parasites, in concentrations high enough to present a health risks;

2. Chemical pollution of dissolved salts (sodium, nitrogen, phosphates, chloride and boron) or by organics (oils, grease, milk, soap, detergents and xenobiotic compounds);

3. Physical pollution of particles (dirt, food, lint) may degrade soil structure, clog groundwater flow paths or cause non-wetting characteristics in soils;

However, risk to consumers can be greatly reduced by crop restriction, modifying irrigation techniques and human exposure [Salukazana et al., 2005].

Caution must be taken before reusing greywater for domestic purposes. It is often used without prior treatment and can spread fecal particles and other organic materials into the surroundings, which exposes individuals to pathogens [Gross et al., 2007].

To prevent the spread of contaminants, a combination of physical filters and aerobic biological processes must be used to remove suspended solids and other hazardous organic materials from greywater. Aerobic filters and bioreactors such as membrane aeration bioreactors (MABR's), biological aerated filters (BAF's), membrane bioreactors (MBR's), and rotary biological contactors (RBC's) are known to be the most effective methods for trapping harmful contaminants [Li et al., 2009].

Greywater that is stored in a tank should also be used within 24 hours. Bacteria and other pathogens can multiply in that amount of time and can turn recycled greywater into blackwater [Dixon et al., 2000]. If the recycled greywater is going to be used to irrigate plants, the use of drip lines, that are placed beneath the soil, must be assured, instead of hoses or misters which are used to spray the water into the air. This will just spread any pathogens present into the air [Allen et al., 2010].

1.4.2 Using Greywater In Irrigation

Recently, there have been various studies carried out to analyze the impacts of reusing greywater for irrigation purposes. Two different schemes can be proposed to apply greywater for irrigating crops, with either treated or untreated greywater. Although each scheme has its own advantages and disadvantages, experiments have shown various results. Several factors should be taken into consideration when a water resource is chosen for agricultural irrigation; plant growth, crop yield, and crop quality. Each factor presents a different trend regarding the irrigation water source.

1.4.2.1 Plant Growth

One can propose to use greywater for irrigation directly without any treatment. However, studies have shown that irrigation with non-treated greywater can reduce plant growth because of the presence of some toxic elements, namely boron (B), chlorides (Cl^-), and cadmium (Cd). Although some compounds present in greywater, such as Phosphate (PO_4^{3-}), are essential for plant growth, high levels of concentration can pollute soil and plants. Therefore, caution must be taken into consideration when irrigating sensitive plants with greywater [Ayers and Westcot, 1994]. In another experiment, plants such as silver beet showed a small reduction in shoot and root biomass when irrigated with untreated greywater compared to a situation when they were irrigated with treated greywater [U. Pinto, 2010].

On the other side, there are some types of plants which show different behavior when irrigated with greywater, compared to irrigation with potable water. Day et al. [Day et al., 1981] showed that cotton grows faster and longer if they are fed with greywater. Similarly, Rusan et al. [Rusan et al., 2007] showed that the presence of essential compounds such as K, N, and P in greywater results in longer cotton plants. They also studied plants such as tomato and lettuce, but reported no significant difference in growth.

Regarding plant growth, studies suggest to treat greywater before irrigation uses. The reason lies upon the presence of toxic elements or compounds in the greywater.

1.4.2.2 Crop Yield

It has been shown, in several researches, that irrigation with greywater increases crop yield, because of the presence of nutrients such as nitrogen and phosphorous in greywater [Rusan et al., 2007]. In a study performed by Day et al. [Day et al., 1981], cotton yield improved when the plant was irrigated with a mixture of untreated greywater and groundwater compared to irrigation with only groundwater. Also in tomato, irrigation with greywater resulted in higher nutrient uptake and biomass at the flowering, comparing to freshwater irrigation [Misra et al., 2009]. Higher yield of some crops is due to higher concentration of nutrients in greywater.

Contrarily, in a study performed in [Al-Zubi and Al-Mohamadi, 2008] in Jordan, there was no yield improvement of tomatoes when they were fed with greywater.

1.4.2.3 Crop Quality

Irrigating with greywater not only impacts the yield, but also the quality of the crops. There are two types of evaluation of the quality of the crops; internal quality, that is, the consumer satisfaction; and external evaluation, which is the analytical evaluation of nutrients and minerals.

Internal evaluation of quality uses various metrics. One of the main metrics is based on individual judgment of customers, known as customer satisfaction. End-users pay more attention to the color and firmness of crops [Shewfelt, 1999] then to its nutritional quality, thus it is not a comprehensive metric. Moreover, such evaluations are mostly subjective [Wagner et al., 1998].

External evaluation of the quality of vegetables also needs to pay more attention to freshness and color quality, besides the nutrient intakes. Wagner et al. proposed a simply scoring system on 1 to 5 scale (or poor to excellent) by merely looking at the size, uniformity and defects [Wagner et al., 1998].

There are few researches studying the external quality of crops being irrigated with greywater. For instance, Day et al. [Day et al., 1981] observed no significant difference between cotton irrigated with greywater and groundwater on the quality of cotton lint. Rusan et al. [Rusan et al., 2007] found that the concentration of lead (Pb) and nickel (Ni) increased as the result of irrigation of wheat with greywater over a period of 10 years. In another research, Zavadil et al [Zuma et al., 2009] studied the effect of irrigating sugar beet with greywater. It was shown that the increase in sodium (Na) concentration can attenuate the leaf chlorosis (brown patches on leaf tips) which decrease the quality of crop.

However, there are crops where irrigation with greywater was found to have positive effects. Rodda et al [Rodda et al., 2011] found that lettuce and spinach irrigated with greywater contain more minerals such as iron (Fe) and zinc (Zn) then similar crops irrigated with potable water. The same effect was also found when barley was irrigated with greywater.

1.5 Greywater Management System

Regarding the reuse of wastewater resources in irrigation, different types of end-users must be considered. Wastewater is commonly treated in centralized facilities and it is reused in both public and private large areas, such as gardens, golf courses and crop productions. Greywater is treated and used in the same site by distributed facilities, with less consumption of energy. Nevertheless, both are reused for the same type of end-uses [Matos et al., 2014].

1.6 Conclusion

Reusing greywater is becoming a common practice in areas that face water scarcity. Greywater includes the water from kitchen, washing machines, dish washer and bathrooms, and can be treated to be used as recycled water. Studies all around the world showed that with proper treatment, greywater from potable uses can be turned into water to irrigation. The risk of exposure of the population in reusing of wastewater or greywater should always be taken into consideration.

The recent interest in reusing greywater has turned toward small-scale distributed treatment facilities. Unlike domestic wastewater, which is treated in centralized facilities, studies have shown that decentralized distributed facilities provide a framework to treat greywater more efficiently [Teh et al., 2015]. The situation beyond, cannot be estimated clearly for most countries, which are not well prepared to struggle with imposed drought caused by climate changes. This phenomenon will economically influence those countries that benefit from agricultural products.

Chapter 2

Greywater: Source, Usage, and Treatment

2.1 Motivation

Many environmental and public health specialists are concerned with either the management of wastewater or the treatment of greywater in developing nations. Some of the literature addressing wastewater use for irrigation, in developing nations, looks only at the issue of untreated wastewater being discharged into surface waters that are used directly for water supply [Qadir et al., 2010]. This is a common situation in most developing cities, which are not equipped with wastewater treatment infrastructures, or where the available infrastructures have been surpassed by population growth. Although this entire system is detrimental to the environment and the human health of those living near this contaminated water, this is not the only option for practicing wastewater irrigation in the developing world, and other wastewater irrigation schemes should not be discarded.

Wastewater contains numerous pathogens that are detrimental to human health and the environment, along with heavy metals, if industrial wastewater is considered to be included [Qadir et al., 2010]. Farmers coming into contact with untreated wastewater, when using it for irrigation, may be exposed to parasitic worms, protozoa, viruses and bacteria [Qadir et al., 2010]. Microbes appear in greywater from fecal contamination, which will likely appear in smaller amounts from laundry and bathing water, and viruses may enter greywater from infected persons [World Health Organization, 2006].

Consuming crops irrigated with wastewater puts a person at higher risk of hookworm, Ascaris sp. infections, and other enteric diseases [Qadir et al., 2010]. However, parasitic protozoa and helminthes are too large to pass through the soil particle matrix and the root structure [Eriksson et al., 2002], and so these pathogens will likely not enter the edible part of the plant. Women will come into contact with the crops more often than any other target group, because they are most likely to be the ones growing, selling and preparing vegetables irrigated with wastewater [Qadir et al., 2010]. Most external contamination would be eliminated by properly washing and cooking vegetables.

In implementing greywater irrigation projects, it is necessary to step back and look at the broader issues of the lack of hygiene, sanitation, and safe food preparation practices in many of these rural areas. Irrigating with wastewater or greywater is not good for all situations or for all plants.

Leafy vegetables, such as lettuce and cabbage, take up much more water than other vines and trees, and nutrients from the water are more likely to be found in the edible portion of the plant [World Health Organization, 2006]. Because they grow closer to the ground, these vegetables are also at higher risk of the edible parts coming in contact with the greywater [World Health Organization, 2006]. Leafy vegetables also accumulate higher levels of certain metals [Qadir et al., 2010]. Root vegetables like yams and cassava should also not be irrigated with urban wastewater, as the edible portion of the plant comes in direct contact with the wastewater. Also, metal concentrations in roots tend to be higher than in leaves [Qadir et al., 2010]. Vegetables that are eaten raw should also not be irrigated with greywater, as cooking vegetables would kill many of the microbes that might reach the edible portion of the plant [World Health Organization, 2006]. Planting in mounds and establishing a furrow irrigation system reduces the risk of plant shoots and edible portions having direct contact with greywater. Certain soils, such as clay, slow infiltration, and greywater may still accumulate at the irrigation site. Adaptations should be made for each situation to provide enough plants or a large enough area for greywater to infiltrate.

In recent years, concerns about the pollution of ground and surface water have been rising [Qadir et al., 2010]. Also, there are concerns about the accumulation of detergent and salts in the soil, in places where prolonged irrigation is performed [Eriksson et al., 2002]. For instance, in the case of the existing wastewater disposal system in Ghana, there is already a risk of contaminating ground water, surface water, and soil. The greywater gardens would help reduce the risk of contaminating these other sources by decreasing ponding. Ideal conditions recommend that the greywater outlet should be at least 1.5 meters above the highest groundwater table [World Health Organization, 2006]. This standard is met in the village of Chirifoyilli, where the groundwater table is about 4 meters below the surface.

Some elements of greywater and wastewater might be harmful to plants. Soap contains alkali salts, and water with high levels of alkali may harm plants [Eriksson et al., 2002]. Detergents contain surfactants and may have additional builders, bleaches, and enzymes, depending on the type of detergent [Eriksson et al., 2002].

2.2 Water Quality Evaluation Parameters

Greywater effluents are categorized mainly by two main parameters: Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The ratio between the two metrics values not only depends on the proprieties of greywater, but also affects any further application of the effluent.

2.2.1 Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) is a measure of the quantity of oxygen used by microorganisms in the oxidation of biodegradable organic matter. Natural sources of organic matter include plant decay and leaf fall. However, plant growth and decay may be unnaturally accelerated when nutrients and sunlight are overly abundant due to human influence. Urban runoff carries pet wastes from streets and sidewalks; nutrients from lawn fertilizers; leaves, grass clippings, and paper from residential areas, which increase oxygen demand. Oxygen consumed in the decomposition process robs other aquatic organisms of the oxygen they need to live. Organisms that are more tolerant of lower dissolved oxygen levels may replace a diversity of natural water systems containing bacteria, which need oxygen (aerobic) to survive. Most of them feed on dead algae and other dead organisms and are part of the decomposition cycle. Algae and other producers in the water take up inorganic nutrients and use them in the process of building up their organic tissues.

2.2.2 Chemical Oxygen Demand

Measurement of COD is the standard method for indirect measurement of the amount of organic pollution that cannot be oxidized biologically in a sample of water.

The chemical oxygen demand test procedure is based on the chemical decomposition of organic contaminants, dissolved or suspended in water. The result of a chemical oxygen demand test indicates the amount of water-dissolved oxygen (expressed as parts per million or milligrams per liter of water) consumed by the contaminants, during two hours of decomposition from a solution of boiling potassium dichromate. Many governments impose strict regulations regarding the maximum chemical oxygen demand allowed in waste water before they can be returned to the environment.

2.2.3 Electrical Conductivity

Electrical conductivity (EC) is the ability of a material to transmit (conduct) an electrical current and is commonly expressed in units of milliSiemens per meter (mS/m). EC measurements may also be reported in units of deciSiemens per meter (dS/m), which is equal to the reading in mS/m divided by 100.

It affects crop yields, crop suitability, plant nutrient availability, and activity of soil microorganisms. Soil EC is affected by cropping, irrigation, land use, and application of fertilizer. Irrigating in amounts too low to leach salts, or with water high in salts, allows salts to accumulate in the root zone which leads to an increase in EC.

2.2.4 Standards

Table 2.1 lists the recommended World Health Organization (WHO) standards for greywater irrigation of food crops. Similarly, to EPA, the WHO also has strict standards for vegetables likely to be consumed uncooked and higher allowable levels for animal food, fruit trees and ornamental use. Many nations have adopted their own set of standards varying from these recommended guidelines. For example, Mexico sets a standard of fecal coliforms$\leq 2,000$*cfu/100mL* (Colony Forming Unit per 100mL) for greywater irrigation, more lenient than the WHO standards. Germany requires fecal coliform≤ 10*cfu/100mL*, stricter than the WHO standards of ≤ 200*cfu/100mL* for vegetables eaten uncooked and the WHO standard of $\leq 1,000$*cfu/100mL* for animal food and fruit trees [World Health Organization, 2006].

The key greywater parameters are listed in Table 2.1. These indicators are the most important because they are the most prevalent in greywater, and significantly impact not only plant growth but also human health. Nitrogen, phosphorous and potassium are important since these are the key elements of fertilizers. Higher levels in wastewater

Table 2.1: quality standards of greywater sample from bath area drain. Table is adopted from [Fagan, 2015].

Parameter	**Unit**	**EPA guidelines (food crop irrigation)**	**WHO standards**	**Average lab irrigation**
Nitrate (NO_3^{-}–N)	*mg/L*	< 5		4.6 (NH_3^{-})
Phosphate (PO_4^{3-})	*mg/L*	2		0.9 (Total)
Fecal coliform	*cfu/100mL*	0	≤ 200	63
BOD	*mg/L*	≤ 10	20	3.5
pH	pH-unit	$6 - 9$	NA	NA
TDS	*mg/L*	NA	$\leq$ 20 (TSS)	2.6 (VSS)

increase the growth of the plant. Nevertheless, if any of these elements is in excess or at non-optimal ratios, they may divert energy to other growth phases, such as increased foliage growth rather than fruit development.

FAO fertilizer report indicates that high levels of nitrogen increase the production of chlorophyll. Although quantity and size of leaves increases due to accumulation of chlorophyll, flower and fruit development will decrease significantly. Besides, root production will be weakened in advance. Excess phosphorus reduces the level of micronutrients a plant can take up from the soil, especially zinc and iron. This insufficiency leads to yellowing or bleaching of leaf tissue. Excess potassium would also affect micronutrient absorption [Food and Agriculture Organization, 2008].

2.3 Worldwide Greywater Reuse

Although greywater could be useful in a variety of ways, as mentioned above, there are some constraints, including widespread acceptance and laws governing greywater quality, that limit its use for irrigation purposes [Mzini, 2013]. In the United Kingdom, citizens prefer to use greywater for toilet flushing, while they are reluctant to use it for washing cars and irrigating the garden [Jefferson et al., 2004]. In contrast, Australians have shown a tendency to use greywater on a wider variety of activities, as long as this

Table 2.2: Typical greywater parameters based on WHO report (*NTU: Nephelometric Turbidity Units). Table is adopted from [Fagan, 2015].

Parameter	Unit	Average Greywater Range (WHO)
BOD	mg/L	$90 - 290$
Nitrate ($NO_3^- - N$)	mg/L	$< 0.1 - 0.8$
Phosphate ($PO_4^{3-} - P$)	mg/L	$0.6 - 27.3$
Sodium	mg/L	$29 - 230$
Turbidity	NTU	22-200
pH	–	$6.6 - 8.7$
Sulfate	mg/L	$7.9 - 110$

avoids direct contact with skin [Marks et al., 2006]. Australians are more comfortable when greywater is used to irrigate public open spaces, than in household uses. Both in the Netherlands and in South Africa, researchers have recommended that greywater should be used in conjunction with other sources of water, because rural and urban users alike consider greywater as unacceptable and unhygienic [Dixon et al., 1999] [Khosa et al., 2003].

Some countries have legislation to govern the greywater usage. In the United States, each state has its own regulation guidelines to the usage of greywater. According to the California Greywater Standards (legislated in 1995), greywater is considered to be less contaminated than blackwater, hence greywater is permitted to be used without treatment for irrigation as long it does not come into contact with humans. In Australia, greywater is permitted to be diverted into the garden by a licensed plumber. This can be done without Council approval except when greywater is treated and stored for flushing toilets or car washing [Society, 2007].

In addition to greywater from the bathing area, wastewater from washing clothing, dishes and other food preparations is often thrown on the ground outside the home and may also accumulate and start to pool. Table 2.2 shows the parameters which the WHO reports are typical for greywater worldwide compared to a sample from a northern Ghanaian village.

These are typical values for greywater, while WHO standards for greywater to be reused will be discussed in the following sections. As shown in Table 2.2, the water from the bath drain in Chirifoyilli falls within the WHO-reported typical range for many of the parameters. The BOD of the bath drain sample is very low, which may be an indication that there is less organic matter in this water than in the average greywater worldwide. The nitrate level of this sample is much higher than the WHO range because of the high urine content in this wastewater [Fagan, 2015].

Nitrification converts the ammonia, from urine in the stagnant wastewater, to nitrite and then to nitrate. Once the sample sat for an undetermined amount of time in the laboratory, prior to testing, nitrification is probably responsible for the high measured nitrate concentration. The sulfate level in the sample may be due to dish washing water, containing salt and food preservatives contributing to the greywater pool. Greywater from the village would not have heavy metals or many of the chemicals found in the greywater of wealthier nations. The population from the village will often use locally made soap rather than mass produced soaps with additives and scents. However, due to small amounts of water used when bathing, washing dishes, and washing clothing, concentrations of contaminants will be much higher in this greywater than the wastewater of wealthier areas with running water to dilute soap and other particles [Fagan, 2015].

2.4 Greywater Treatment Technologies

Recent technologies to treat greywater can be classified as physical, chemical, and biological systems, or even a combination of these [Li et al., 2009] [Ghunmi, 2011] [Boyjoo et al., 2013]. Most of these technologies include three different individual steps: pre-treatment, main treatment, and post-treatment, as shown in Figure 2.1. Pre-treatment, such as septic tanks, filter bags, screens and filters, are essentially required to avoid blocking pipes or to reduce the number of particles, oil and grease [Li et al., 2009]. Post-treatment is required to disinfect, removing microbiological elements from the treated greywater flow [Albalawneh and Chang, 2015].

2.4.1 Biological Greywater Treatment Systems

There are various biological treatment systems used to treat greywater: Rotating Biological Contactor (RBC), Sequencing Batch Reactor (SBR), Membrane Bioreactors (MBR), Fluidized Bed Reactor (FBR), and Upflow Anaerobic Sludge Blanket (UASB).

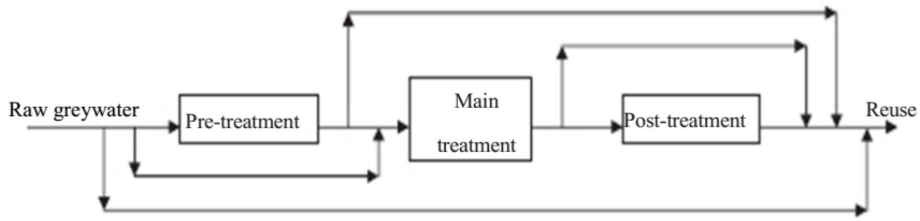

Figure 2.1: Graywater recycling and treatment: possible steps and tracks. Figure is adopted from [Ghunmi, 2011].

Biological treatment systems normally present three stages: coarse filtration as pre-treatment; sedimentation/filtration to remove bio-solids or sludge; and a disinfection post-treatment stage, using chlorination or UV, to remove microorganisms, at the end [Boyjoo et al., 2013]. It has been reported that using aerobic biological processes increase the quality of the final effluent, because of excellent organic matter removal and turbidity decreasing rate. The mentioned processes make the treated greywater more stable for storage during longer periods.

The MBR is known as an effective system for greywater treatment because it achieves a satisfactory removal efficiency of organic substances, surfactants, and microbial contamination, regardless of the requirement for the post-filtration step. The MBR combines bio-degradation with membrane filtration for solid-liquid separation. MBR systems achieve efficient removal rates: turbidity ($98 - 99.9\%$), TSS (around 100%), BOD ($93-97\%$), COD ($86-99\%$), total nitrogen (N) ($52-63\%$), PO_4^{3-} (10-40%), total phosphorous (P) (19%), and fecal coliform (FC) (99.9%); [Ghaitidak and Yadav, 2013]. Evaluations show that the quality of the MBR effluent satisfies various standards [Pidou et al., 2007] [Boyjoo et al., 2013] [Bani-Melhem et al., 2015]. Merz [Merz et al., 2007] named this technology investable and operational due to costs for developing countries.

The RBC and FBR systems were found to be efficient for treating light greywater [Nolde, 2000]. The RBC system requires lower maintenance, if the number of stages is increased (while keeping the same volume). Friedler reported that RBC is more efficient to remove BOD than COD [Friedler and Hadari, 2006].

The SBR system is a special form of activated sludge processing, meaning that all the treatment stages are performed in the reactor tank. Using a time-controlled sequence, SBR carries out equalization, biological treatment, and secondary clarification in the same place. It is known to be one of the best technologies for the removal of conventional parameters in small scale. Effluent from SBR treatment [Lamine et al., 2007] of shower greywater meets the NH_4-N, BOD, and COD standards for wastewater reuse; BOD removal varied from 80 to 98% and similar ranges of COD removal were observed. There is no information concerning the efficiency of SBR systems to improve parameters like turbidity, TSS, TC, FC, and *E. coli* [Ghaitidak and Yadav, 2013].

All in all, anaerobic treatment performs a poor job removing both organic substances and surfactants [Leal et al., 2011]. Only 40% COD removal was achieved using an HRT with a UASB for $12-24$ hours. It has been recommended by Ghunmi that using anaerobic pre-treatment significantly improves the quality of the effluent, [Ghunmi, 2011]; this is regardless of the disinfection stage, which is required to remove biological pathogens from the effluent. Anaerobic treatment is low cost and simple [Halalsheh et al., 2008]; however, aerobic treatment provides a better alternative in order to remove toxic components in greywater [Leal et al., 2011] [Albalawneh and Chang, 2015].

2.4.2 Physical Greywater Treatment Systems

Physical greywater treatment systems include two stages: filtration and sedimentation. Filtration is a stage which is used in both pre-treatment or as a post-treatment method. Filtration as a pre-treatment method includes screen meshes, sand bed filtration, nylon sock type filtration, metal strainers, gravel filtration, and mulch tower system [Boyjoo et al., 2013].

Using physical greywater treatment processes as the main treatment method has been proved to be insufficient, because it does not guarantee disinfection and reduction of nutrients and surfactants. The efficiency of the filtration techniques depends on the size of the pollutants and the filters' porosity; in general, the smaller filters provides better effluent quality. [Li et al., 2009] [Ghunmi, 2011] [Boyjoo et al., 2013] [Ghaitidak and Yadav, 2013].

Chaillou [Chaillou et al., 2011] studied the efficiency of a sand bed filtration to treat bathroom greywater. On average, the method was able to remove 30% COD and two log *cfu/100mL E. coli*. In another research, Zuma [Zuma et al., 2009] observed that a mulch tower system, coarse sand, fine gravel, and coarse gravel was able to remove almost 26% of COD and 52% of TSS, however they showed that their methodology was not so efficient to reduce the level of FC and total coliforms, since they remained unchanged. There are some physical filtrations wich are able to produce a high quality effluent. Membrane filtration, microfiltration (MF), ultrafiltration (UF) and nano-filtration (NF); [Shin et al., 1998] [Ramona et al., 2004] are some examples of methodologies which are proportional to the molecular weight cut-off (MWCO) of the membrane. UF membranes with pores in the range $30 - 200kDa$ have been reported to filter between $92 - 97\%$ and $45 - 70\%$ of turbidity and organic matter, respectively. Ramona et al. [Ramona et al., 2004] treated shower water via NF, and the removal of COD, TOC, and soluble ionic species was 93%, 84%, and 50%, respectively. The filtration obtained with NF membranes has better quality, as they remove soluble components, including organic matter, pathogens, ionic species, and even some kinds of viruses [Ramona et al., 2004].

Alongside to the advantages, filters imply dealing with some issues such as cleaning. Unfortunately, membrane operation and maintenance costs can restrict the application of membrane technologies for greywater treatment. In this case, inexpensive solutions such as pretreatment of raw greywater in storage and settling tanks, partially can mitigate the clogging problems [Li et al., 2009] [Ghaitidak and Yadav, 2013] [Albalawneh and Chang, 2015].

2.4.3 Chemical Greywater Treatment Systems

Unlike the physical strategies, the chemical processes are able to reduce organic matter and turbidity in greywater to a certain degree, but not enough to meet the non-potable reuse standards [Li et al., 2009] [Boyjoo et al., 2013]. Some of the methodologies used in chemical greywater treatment systems are: coagulation and flocculation, electro-coagulation, adsorption using granular activated carbon (GAC) and natural zeolites, magnetic ion exchange resin (MIEX), powdered activated carbon (PAC) and advanced oxidation processes (AOPs) such as ozonation, and photocatalysis [Li et al., 2009] [Boyjoo et al., 2013]. These systems are efficient for use with light greywater and, in some cases, laundry greywater; however, they are not able to satisfy the standards required for potable usages [Li et al., 2009] [Boyjoo et al., 2013] [Albalawneh and Chang, 2015].

Pidou [Pidou et al., 2008] investigated the use of a coagulation/flocculation treatment system for shower greywater. They achieved sufficient levels of organics and coliforms removal. They achieved BOD removal of 85 to 89%, COD removal around 64%, TC removal $> 99\%$, and *E. coli* removal $> 99\%$; however, their method did not successfully remove Nitrogen (N), only up to 13%. It was reported that the proposed system provided better results in acidic pH, which requires adjusting the pH after treatment.

Unfortunately, adjustment of pH before and after treatment would increase the cost of the system, which can be noted as a drawback for its application [Ghaitidak and Yadav, 2013]. A flocculation system using aluminum sulfate [Kariuki et al., 2011] had no effect on pH, salinity, and electrical conductivity in both kitchen and laundry greywater. Nevertheless, flocculated greywater could not meet reuse standards.

Lin [Lin et al., 2005] carried out a research to show the effectiveness of electro-coagulation at treating shower greywater. The coagulant was produced from the evolution of Al^{3+} at the aluminum anodes. Hydrogen was produced at the cathodes and the bubbles allowed the particles to float, which were then skimmed out in a separate vessel. Besides, another disinfection stage using sodium hypochlorite was essential to eliminate *E. coli* in the treated effluent. Evaluations showed that the water quality obtained satisfied the general standards for non-potable reuse. The system capacity was $28m^3/d$, had a footprint of only $8m^2$, and a total cost of \$0.27/m^3 [Lin et al., 2005].

Sanchez [M. Sanchez, 2010] successfully removed almost 65% of the dissolved organic carbon from hotel light greywater using photocatalysis with titanium dioxide. Photocatalysis with titanium dioxide (TiO_2) catalysts was shown to be an efficient post-treatment method for the biologic organic matter removal [Li et al., 2004] [Gulyas et al., 2007]. Photocatalysis consists of the use of a catalyst, UV light, and an oxidant, to oxidize organic pollutants in a solution. The disinfection step is not required, since photocatalysis can greatly reduce pathogens in water [Li et al., 2004]. Although they were successful in the treatment, it was important to remove the TiO_2, and this makes the process more expensive [Ghunmi, 2011] [Albalawneh and Chang, 2015].

State of the art reviews revealed that the combination of chemical processes (such as coagulation), followed by a filtration and/or disinfection stage, can reduce the suspended solids, organic substances, and surfactants in low-strength greywater to an acceptable level that can meet non-potable urban reuse requirements [Lin et al., 2005] [Pidou et al., 2008]. However, for medium and high strength greywater, the system is not always able to provide the required reuse standards in all situations, unless these processes are combined with other processes [Pidou et al., 2008]. To meet restricted non-potable urban reuse standards, the effluent from the chemical processes can be treated with physical process (such as sand or membrane filtrations) [Li et al., 2009] [Ghaitidak and Yadav, 2013] [Albalawneh and Chang, 2015].

2.4.4 Natural Greywater Treatment Systems

Natural greywater treatment systems are categorized as systems which use natural media for filtration and biological degradation (i.e., soil and plants). Followed by a disinfection stage, these systems can be used to treat heavily polluted greywater [Boyjoo et al., 2013]. These systems combine physical processes, such as filtration through a filter medium (i.e., sand, gravel, rocks, cinder) with biological processes such as aerobic or anaerobic degradation, via microorganisms found within the system (i.e., biofilm, plant roots, slugs, earth- worms). Some examples are sand filter, horizontal-flow constructed wetland (HFCW), vertical-flow constructed wetland (VFCW), anaerobic filters, and vertical-flow filter (VFF). Also, nutrient uptake in planted systems (in the method of VFCW, HFCW) has a filtering impact concerning nutrient removal. Therefore, it is known as the most environmentally-friendly and cost-effective technology for greywater treatment and reuses [Li et al., 2009] [Ghaitidak and Yadav, 2013]. Although these systems are considered preferable due to their low cost [Boyjoo et al., 2013], they also require a large surface area $(0.5-3m^2)$ per person. Therefore, they are not suitable for use in urban areas. Evaluation shows that wetland treatment systems achieved TSS removal rates of $90-98\%$, BOD $> 99\%$, COD from 81 to 82%, total N from 26 to 82%, B from 0 to 63%, and K up to 67%. No removal was observed for Ca, Mg, and Na [Albalawneh and Chang, 2015].

Constructed mini wetlands (i.e., small-scale constructed wetland system or SSWL) were found to be effective at removing contaminants and suitable for treating greywater sources [Wurochekke et al., 2015]. SSWL is designed on special ecological principles to maximize the function of relevant ecological processes within a limited area. Unlike the large-scale constructed wetland, the SSWL cannot afford the services of a full-time dedicated maintenance staff [Albalawneh and Chang, 2015].

2.4.5 Greywater Recycling Scheme for Agricultural Reuses

Based on the review of greywater characteristics, guidelines requirements, and greywater treatment technologies, a greywater recycling scheme for agricultural irrigation reuse purposes can be developed [Albalawneh and Chang, 2015]. Depicted in Figure 2.2, the proposed scheme is based on Li et al. [Li et al., 2009] scheme of greywater recycling for non-potable urban reuses.

Li et al. [Li et al., 2009] defined unrestricted greywater reuse as its use in recreational impoundments, toilet flushing, laundry, air conditioning, landscape irrigation, fire

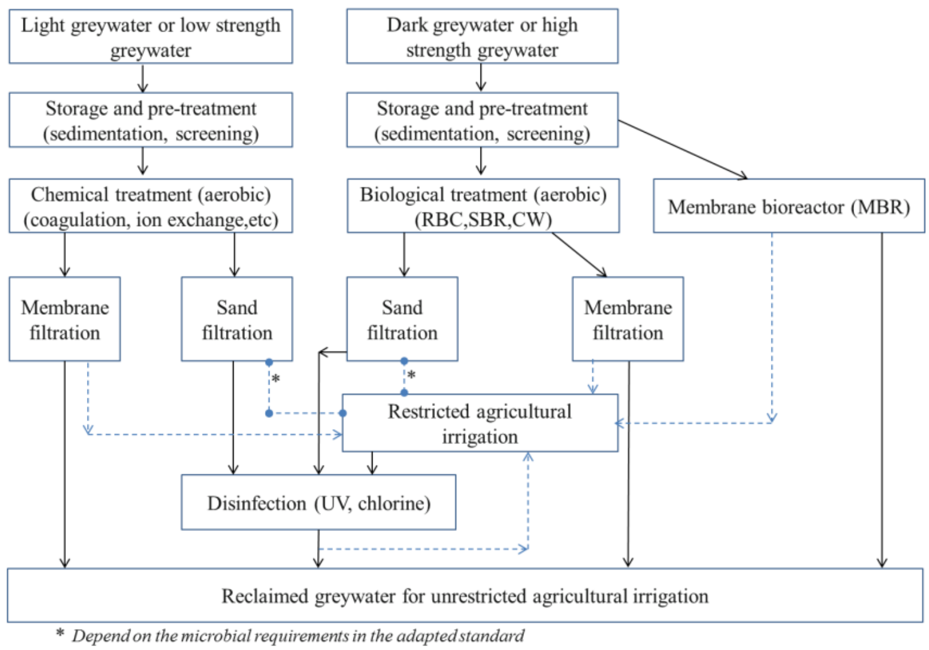

Figure 2.2: Possible greywater recycling scheme for agricultural irrigation reuse purposes. Figure is adopted from [Albalawneh and Chang, 2015].

protection, construction, surface irrigation of food crops and vegetables (consumed uncooked), and street washing. Restricted greywater reuse includes lakes and ponds for recreational uses (without body contact), landscape irrigation, where public access is infrequent and controlled, such as subsurface irrigation of nonfood crops, food crops, and vegetables that are consumed after processing [Albalawneh and Chang, 2015].

As shown in Figure 2.2, the greywater is equalized in a storage tank to cope with the variability in influent. It is essential to remove larger particles before feeding it into the treatment processes [Li et al., 2009]. To meet the requirements of restricted and unrestricted agricultural irrigation, chemical solutions are applied by membrane filtration to treat low-strength greywater. Considering microbiological standards, effluent from the chemical processes can be further filtered by sand. Additionally, disinfection stage follows, with the application of sand filtration. This step is required to improve the quality of the reclaimed greywater, for both restricted and unrestricted irrigation [Albalawneh and Chang, 2015].

The proposed strategy is not sufficient for medium and high-strength greywater, because an appropriate biological process is required to remove organic substances. These stages could be combined with the membrane filtration post-treatment, to meet the requirements of restricted and unrestricted agricultural irrigation [Albalawneh and

Chang, 2015].

2.5 Systems for Garden Greywater Reuse

Greywater reuse for disposal purposes is different from reusing it for irrigation. Greywater for irrigation is stored in a storage tank and allowed to run through subsurface irrigation drip lines placed through garden beds.

The method proposed in [Ng, 2004] is useful for larger plants or trees that have roots deep enough to access the water coming from the pipes or trenches. Since water may drain too rapidly in sandy soils, this method can provide an additional benefit to the vegetation.

In their system, plants are only irrigated when required, instead of the water running through the trenches each time the tank fills.

The study done by [Ng, 2004] is focused on an approved greywater reuse system for irrigation purposes. The system is installed in a suburban family home and collects greywater from a family of four to distribute the treated greywater for subsurface irrigation under the lawn. The system consists of three major components including a pre-treatment stage (a split plumbing system); a treatment stage (a greywater tank, disk filter, and electric pump); and finally a network of subsurface drip irrigation lines as distribution lines. These components are described briefly as follows.

2.5.1 Split Plumbing System

The plumbing system of a residence with three bedrooms and two bathrooms is split to separate greywater from wastewater. The greywater was collected from baths, showers, washbasins, and washing machine/laundry were directed to the storage tank of the pre-treatment stage.

2.5.2 Tank, Pump and Filter

The system treats greywater to a primary level before it is pumped through the subsurface drip lines. Pre-treatment is a form of physical treatment aimed at reducing wastewater speed in order to settle out solids. The low-density polyethylene tank has

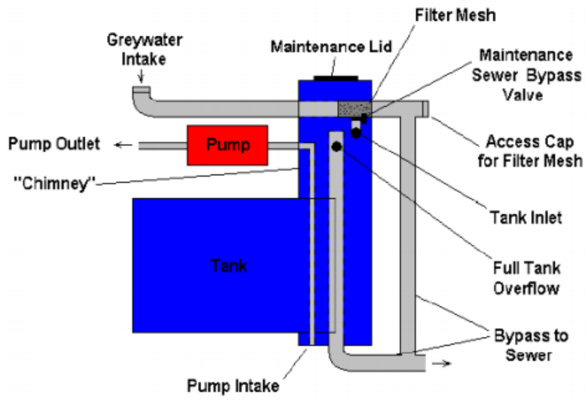

Figure 2.3: Schematic diagram of the greywater tank and plumbing. Figure is adopted from [Ng, 2004].

a capacity of approximately 205 liters sufficient for overflowing main sewer. During irrigation events, the greywater is drawn from the bottom of the tank by an electric pump and passes through a disk filter, flow meter, and slow release chemical root intrusion cartridge, before it reaches the irrigation network. The disk filter is used to hinder lint and hair from blocking the irrigation network. Besides, using the root intrusion chemical prevents grass roots from blocking the irrigation network under the lawn. The tank, pump and filter set-up are shown in Figure 2.3.

2.5.3 Subsurface Irrigation Network

Subsurface irrigation allows greywater to be reused without any personnel contact. The proposed irrigation distribution system consists of ten parallel lines of NETAFIMTM drip irrigation piping, approximately five centimeters below the ground surface. Each row is approximately $30cm$ apart and each dripper is $40cm$ apart along the irrigation line. Figure 2.4 shows the layout of the lawn and irrigation network.

2.6 Crop Irrigation with Untreated Greywater

In a study by Finley et al. [Finley, 2008], they tried to study the effects of irrigating crops with greywater directly collected from household. In this manner, they provide three types of water, including tap water, untreated greywater, and treated greywater. Moreover, they investigated three types of plants to evaluate the direct contact of edible part with soil.

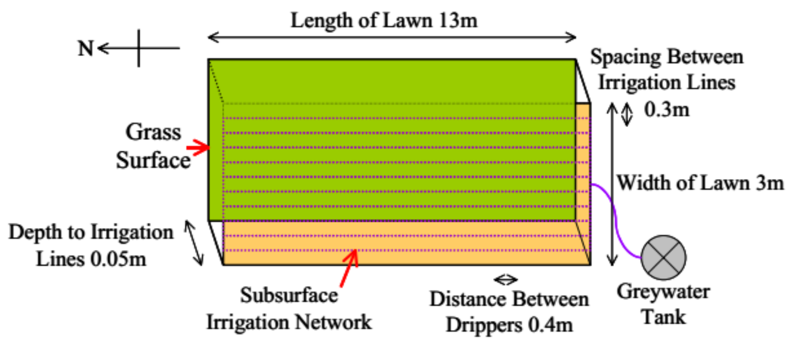

Figure 2.4: Layout and dimensions of subsurface irrigation network and irrigated lawn. Figure is adopted from [Ng, 2004].

2.6.1 Experimental materials

Greywater of the showers and washing machine of a household for a single family was sampled by sampling containers at two locations within a home greywater collection or treatment system.

The first sample (which is untreated greywater or GWu) was obtained after a primary settling stage with a hydraulic retention time (HRT) around 8h, while the second sample was related to treated greywater (GWt) that was obtained after coarse filtration and treatment by slow sand filtration with a HRT of $\pm 24h$.

Regarding the sources of greywater, it was reported that they were collected of two showers, one bathtub, and one washing machine. The house is inhabited by a family consisting of three adults and one small child. The residents use environmental friendly shampoos and detergents, and diapers were not washed in the machine that flows into the greywater system (biodegradable, phosphate free). The characteristics of the greywater and tap water used for irrigation purposes in this study are outlined in Table 2.3.

Potting soil used in the experiment was obtained by mixing 7.5 parts of pasteurized field top soil (mainly of fine sand), one part from perlite, one part from vermiculite, and half of part of peat moss (sphagnum moss).

The following plants and seeds were used in the experiment: baby finger carrots, *Daucus carota sativa*; grand rapids lettuce, *Lactuca sativa*; and gypsy red peppers, *Capsicum annuum*. Three types of plants were categorized as:

- The carrots represented the category of root vegetables.

Table 2.3: Experimental greywater and tap water used for irrigation. Table is adopted from [Finley et al., 2008].

Parameter	**Untreated greywater** (GW_u)	**Treated greywater** (GW_t)	**City of Montreal tap water**
pH	$6.7 - 7.6$	$6.9 - 7.9$	$7.4 - 7.5$
TS (*mg/L*)	$313 - 543$	$330 - 633$	ND
COD (*mg/L*)	$278 - 435$	$161 - 348$	ND
NH_4–N (*mg/L*)	$1.2 - 6.2$	$4.1 - 5.1$	ND
P (*mg/L*)	$0.24 - 1.02$	$0.24 - 1.21$	ND
K (*mg/L*)	$2.2 - 2.5$	$0.6 - 4.4$	ND
Al (*mg/L*)	ND	ND	ND
Ca (*mg/L*)	$30 - 44$	$28 - 44$	$9.5 - 9.6$
Cd (*mg/L*)	ND	ND	ND
Co (*mg/L*)	ND	ND	ND
Cr (*mg/L*)	ND	ND	ND
Cu (*mg/L*)	ND	ND	ND
Mg (*mg/L*)	$8.0 - 9.9$	$8.0 - 10.1$	2.1
Mn (*mg/L*)	ND	ND	ND
Mo (*mg/L*)	ND	ND	ND
Na (*mg/L*)	$20 - 27$	$18 - 27$	$18.6 - 18.8$
Pb (*mg/L*)	ND	ND	ND
S (*mg/L*)	$5.0 - 8.8$	$3.3 - 8.0$	$6.8 - 7.0$
Fe (*mg/L*)	0.09	$0.08 - 0.45$	ND
Zn (*mg/L*)	$0.04 - 0.42$	$0.01 - 0.38$	ND
SAR	$4.2 - 5.8$	$3.9 - 6.1$	$7.7 - 7.8$
Fecal coliform (*cfu/100mL*)	$4.7 \times 10^4 - 8.3 \times 10^5$	$2.2 \times 10^4 - 1.4 \times 10^6$	ND
Fecal streptococci (*cfu/100mL*)	$110 - 3.8 \times 10^5$	$170 - 8 \times 10^2$	ND

Figure 2.5: Greenhouse experimental setup with each pot containing three plants and triplicate pots per treatment. Figure is adopted from [Finley et al., 2008].

- The lettuce represented leafy vegetables with close soil contact.
- The peppers represented crops that mature off the ground with limited soil contact.

2.6.2 Methodology of the Experiment

The duration of the experiment was reported to be around 8 weeks. Both treated and untreated greywater were obtained weekly from the containers and characterized for nutrients (N, P, and K), pH, heavy metals, and indicator organisms (fecal coliforms and fecal streptococci).

The statistical design consisted of applying one of the three sources of water (3 choices), tap water, untreated greywater, or treated greywater, to triplicate pots (3 choices) of each plant type (3 choices), for a total of 27 experimental blocks. Figure 2.5 depicts a block used in the experiment.

The greenhouse compartment remained under standard local conditions of temperature and humidity. Plants were spread randomly and irrigated daily with $300mL$ of either tap water or one of the two greywater samples (GW_u or GW_t) at the same time. It should be noted that irrigation was performed manually by directly applying the water to the soil surface while it was tried to avoid any contact of the water with plant surfaces. Plants were watered 6 days per week, first 5 days with samples, no watering on the sixth day, and briefly sprayed freshwater on the last day. All blocks were fertilized with the recommended dosage of slow-release fertilizer.

For lettuce, the time span from planting to harvest took 55 days, for carrots 65 days, and for peppers 75 days. Upon maturity, the edible portion of each plant type was harvested in three successive batches taken on separate days. In the laboratory, 50g samples of each crop were cut into small pieces using sterile scissors and immersed in sterilized solvent. The resulting elution was shaken and tested for fecal coliforms and fecal streptococci according to the method outlined in Collins [Collins, 2004] for the microbial evaluation of fresh foods. The results are discussed in section 3.1.

2.7 Irrigation with Treated Greywater

Using greywater directly to irrigate crops (untreated greywater) has been studied in many researches. In situations where the quality of untreated greywater does not fulfill the requirements, or it contains compounds which may affect the crops, it is essential to improve the quality of greywater to be able to use it in irrigation. Al-Hamaiedeh and Bino [Al-Hamaiedeh and Bino, 2010] analyzed the effects of irrigating crops (both plants and soil) with treated greywater. The results are presented in section 3.2.

2.7.1 Materials and Methods

In this study, [Al-Hamaiedeh and Bino, 2010], a 4-barrel and confined trench (CT) units were used for greywater treatment. Depicted in Figure 2.6, a 4-barrel unit is constructed from four plastic barrels made from high density polyethylene (HDPE). The depicted barrels are used in order to treat the greywater if a household.

The process of treatment is started by providing stored greywater into the first stage. In the first barrel, the floating grease, oil and small solids are removed. The second and third barrels are filled with gravel filter media of 2 to 3cm diameter. They are connected in order to pass the water through them in an upward fashion. The fourth barrel was fitted with a small electric pump and a float switch to pass the treated

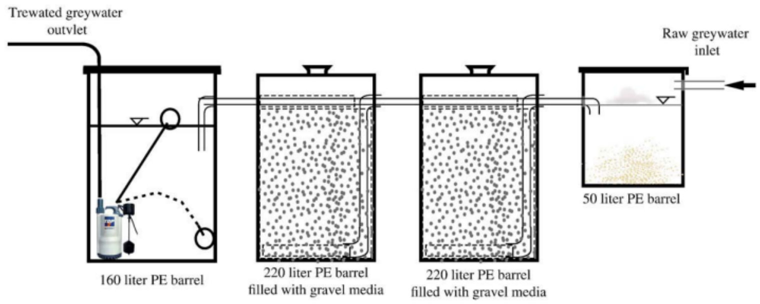

Figure 2.6: 4-barrel treatment unit. 1-first barrel; 2-second barrel; 3-third barrel; 4-fourth barrel. Figure is adopted from [Al-Hamaiedeh and Bino, 2010].

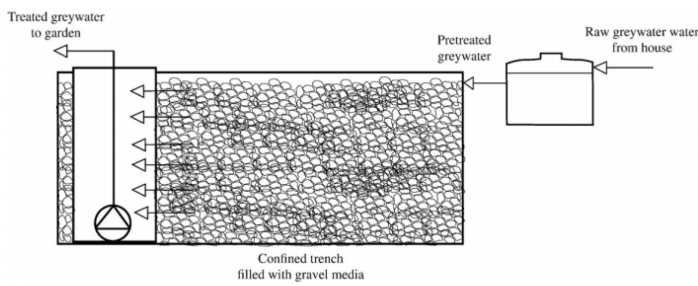

Figure 2.7: Confined trench treatment unit. 1- first barrel; 2- confined trench; 3-barrel; 4- submersible pump. Figure is adopted from [Al-Hamaiedeh and Bino, 2010].

greywater to an irrigation system.

Small modifications were done in the CT unit as shown in Figure 2.7. The modification was accomplished by replacing the second and third barrels with a dug trench of about $3m^3$ capacity, filled with a gravel media and lined with thick impermeable plastic sheet. This modification resulted in increasing the unit hydraulic load [Al-Hamaiedeh and Bino, 2010]. Treated greywater was pumped through a trickle irrigation system to home garden.

2.7.2 Study Area

The study area was at Al-Amer villages in Karak in the middle part of Jordan. Dominated by the Mediterranean climate, the studied region is characterized by dry and hot summer seasons with a max temperature of $34°C$ and wet winter season with a mean temperature of $14°C$. The population in the study area was estimated to be about six thousand in 2006 [Al-Hamaiedeh and Bino, 2010].

Table 2.4: Analysis methods. Table is generated from [Al-Hamaiedeh and Bino, 2010].

Detection of	**Method**	**Details**
Concentration of TSS	Drying	At $103-105\ ^\circ C$ described by standard methods 19th edition 2540 D
Nitrogen	Kjeldahl Method	Standard methods 19th edition 5210 D
BOD	5-day BOD test	Standard methods 19th edition 5210 D
COD	Closed reflux, titrimetric method	Standard methods 19th edition 5220 D
Cd and Pb	Atomic absorption spectrophotometer	Spectrophotometer equipped with a graphite furnace (Perkin Elmer; Model Analyst 300)

2.7.3 Greywater

Using graduated barrels, the average daily flow rate of treated greywater produced from five households was measured. Flow measurement was carried out in 2006 on a weekly basis and lasted for six months. Raw greywater samples were taken from barrels that received water over 24 hours while treated greywater samples were collected from barrels that received treated greywater. In order to make sure about having no contaminants, the barrels were cleaned before greywater collection while the contents of the barrels were mixed thoroughly before sampling. Besides, sampling bottles were washed in diluted hydrochloric acid before usage.

After sampling all the collected samples were analyzed for multiple analysis, including pH, TSS, BOD, COD, total nitrogen (T−N), nitrate as well as cadmium Cd and Pb, by considering all the standards of analyzing wastewater [American Public Health Association, 1995]. The authors provided the analysis methods listed in Table 2.4.

2.7.4 Soil Quality and Texture

According to the United States Department of Agriculture (USDA) soil texture classification, the soil texture of the experiment was classified as silty clay [Foth and Ellis, 1997]. Soil sampling was conducted twice a year for two years. The samples were

Table 2.5: Soil analysis methodologies. Table is generated from [Al-Hamaiedeh and Bino, 2010].

Measuring	**Method**	**Details**
Soil paste extract salinity (dS/m)	Conductivity meter	ORION model 160
Ca and Mg	EDTA titration method	-
Na^+	Flame atomic absorption spectroscopy	Spectra Atomic Absorption 800 Varian
Organic Matter (OM)	Dichromate method	

collected from five designated home gardens irrigated with greywater. Six soil samples were collected from each garden irrigated with greywater: three of the samples were collected from the surface layer at depths of 0 to $30cm$ and the other three were collected at depths of 30 to $60cm$. Authors also noted that the reference samples were collected two years before the irrigation experiment, from the same gardens.

To preserve samples for further analysis, they were dried, sieved for $52mm$ and stored at $-20°C$ until time of analysis. During the experiment, authors performed soil analysis including SAR, electrical conductivity, and organic matter content according to standard methods [Association of Official Agricultural Chemists, 1989]. The details of the Soil analysis are listed in Table 2.5.

2.7.5 Plants Leaves and Fruits

Composite samples of fresh olive leave and fruits were collected from five gardens irrigated with greywater. Aforementioned samples were collected from each garden annually during two years. To provide reference samples, the same number of olive leaves and fruit samples were collected from the same gardens two years before the greywater irrigation experiment. Vegetable crops okra, bean, corn, and sunflower were planted in one home garden and upon maturation five fruit samples and five leaf samples from each crop were collected. The authors conducted the measurement of nitrogen, phosphorus, potassium, sodium, chloride, cadmium, and lead. Leaves and fruits were first washed with distilled water, dried at $50°C$ until constant weight and then the samples were homogenized. Dissolving $0.2g$ of each sample in $10mL$ of solvent. It was covered with a watch glass, and the contents were boiled on a hot plate for approximately 30 *min*. The contents were then evaporated to near dryness.

The provided and prepared sample obtained was analyzed for Cd and Pb using an atomic absorption spectrophotometer equipped with a graphite furnace. To measure the concentration of Na^+ and K^+, flame atomic absorption spectroscopy (Spectra Atomic Absorption 800 Varian), was performed whereas Cl^- and P were analyzed using ion chromatography and N content was measured by Kjeldahl Method.

2.8 Passive Irrigation with Greywater

The main objective of the work done by Fagan [Fagan, 2015] was to understand the possibility of using greywater in rural areas for crop irrigation. They studied the growth of tomato being irrigated with greywater effluent from a household in the village of Chirifoyilli, Ghana. In the following paragraphs, the required steps for their investigation are presented, while the results and discussions are provided in section 3.3.

2.8.1 Brief of Method

Planting beds were assembled to simulate the greywater garden schemes from the Peace Corps project. Secondary effluent from a local wastewater treatment plant was used as a greywater substitute. Beds were planted with tomato cultivars with similar characteristics to those found in Ghana. Silty clay was used as a growth medium to simulate the clay soil found in Northern Ghana [Fagan, 2015].

Seeds were planted in batches of 12 between July 14 and August 4, 2015. This gave the plants the 8 to 10-week establishment and early development time as recommended by tomato growers [Fagan, 2015]. Healthier plants were transferred into $6-inch$ pots when they reached heights of 5 to 10 inches. Tomato plants were transplanted to the planting beds between October 6 and 9, 2015. Plants were measured when initially transplanted to beds and every 5 days after. Plants were harvested and final measurements taken between December 10 and 19, 2015, which was $63-72$ days after they were transplanted to the beds. Tomato plants were grown under similar conditions in a greenhouse, irrigated with high volumes of the greywater substitute, high volumes of fresh water, or low volumes of fresh water.

Tomatoes were grown in three different variable groups, which are described in more detail below. The variables were chosen to determine whether the effect on plant growth was caused by a higher volume of water alone or by the combination of high volume and added nutrients. The plants were measured throughout the growth process, and a final measurement after harvest was taken to determine the effect of these variables on the growth rate. Table 2.6 shows the parametric measurement of greywater from the experiment.

Table 2.6: Measurement of greywater metric form Fagan experiment. Table is adopted from [Fagan, 2015].

Parameter	**Unit**	**Ghana Bath-area Wastewater**
Nitrate (NO_3^-−N)	*mg/L*	13.73
Phosphate (PO_4^{3-})	*mg/L*	10.63
Potassium	*mg/L*	64
Fecal coliform	*cfu/100*	28×10^4
BOD	*mg/L*	14
pH	-	7.95
TDS	mg/L	774.9
Dissolved Oxygen	*mg/L*	14.5
COD	*mg/L*	1915
Total coliform	*cfu/100*	482×10^4
E. coli	*cfu/100*	11×10^4

In order to use water similar to the greywater used in the field, this experiment used secondary effluent wastewater that had already been through a settling tank where most solids have been removed and through biological treatment, but prior to chemical disinfection. The goal was to achieve similar levels of nitrogen, phosphorus and BOD to those found in the Ghana wastewater sample. Due to the different laboratories performing tests for different indicators, the parameters tested do not match exactly between the Portage Lake Wastewater Treatment Plant in Houghton, Michigan and the Savannah Agriculture Research Institute in Tamale, Ghana. The water quality parameters for the different water sources are shown in Table 2.7.

Since the wastewater treatment plant measures ammonia rather than nitrate, or total nitrogen, it is difficult to determine the levels of nitrate in the secondary effluent sample used. Ammonia (NH_4^+−N) oxidizes to nitrate (NO_3^-−N) during the treatment process as part of the nitrification cycle [Fagan, 2015], as shown by the drop in

Table 2.7: Water quality of sample from wastewater treatment plant and field greywater. Table is adopted from [Fagan, 2015]

Parameters	**Influent Wastewater WWTP**	**Secondary Effluent WWTP**	**Ghana bathing area Greywater**
Temperature ($^\circ C$)	12.7	NA	25
pH	7.6	NA	7.95
Nitrogen (mg/L)	20.1 (NH_3–N)	4.6 (NH_3–N)	13.73 (NO_3–N)
Total Phosphate (mg/L)	2.9	0.9	10.63 (PO_4–P)
BOD (mg/L)	154	3.5 (CBOD)	14
VSS(mg/L)	136	2.6	774.9 (TDS)
Fecal Coliform (*cfu/100mL*)	NA	63	2.8×10^4

ammonia from influent to secondary effluent in Table 2.7. Ammonia levels decrease over time as nitrate levels increase. Thus, ammonia levels will serve as an indication of the presence of nitrogen in the wastewater assuming it will oxidize to nitrate, the form of nitrogen most readily taken up by plant roots in soil [Fagan, 2015]. Phosphates, specifically polyphosphates, are sometimes used as an ingredient in detergents. Lower levels of phosphates were measured in the secondary effluent from the wastewater treatment plant because polyphosphates have been banned as a detergent builder in the US, but are likely still present in some soap found in Ghana. In addition, phosphates would have precipitated in the aeration basin in a treatment step prior to collection at the wastewater treatment plant [Fagan, 2015].

At the time of harvest, each plant was measured for height and leaves were counted a final time. The plant was carefully removed from the soil, keeping the root structure intact. The root was rinsed in a tub of water to remove soil still attached to the root. The root mass was measured for length. Each plant was then cut at its soil line, and the root and the top shoot were weighed separately. The root and shoot were then labeled and placed in an oven at $38^\circ C$ for 12 hours. At the end of the oven cycle the plants were removed, and the dry root and dry shoot were weighed.

2.9 Irrigation with Domestic Greywater

Rodda et al. [Rodda et al., 2011] carried out a research to analyze the impact of greywater irrigation on plants. To have a comprehensive analysis, they designed an experiment to use three types of water on two different types of plants. In the following paragraphs, their experimental methodology is briefly explained. The results of their experiment are presented in section 3.4.

2.9.1 Materials and Methods

2.9.1.1 Experimental Design

Eight households in Cato Crest, were selected for the collection of mixed domestic greywater. Factors such as the number of people per household, ages, gender and washing applications (bath, hand basin, laundry and dish washing) were considered to select the households for the experiment. The total number of residents in the selected households was 53 persons, including 37 adults ($18 - 100$ years), 12 children ($2 - 18$ years) and 4 infants ($0 - 2$ years). eThekwini Municipality took responsibility to collect greywater daily at household (Monday-Friday). The researchers also noted that the collected greywater from households were mixed in the collecting container on site. No pre-treatment was performed on the greywater before the experiment; however, it was sieved through a metal mesh in order to remove large particles which might block the outlet pipe of the container.

2.9.1.2 Plant Type

Two types of plants were studied in their research. Representative vegetable crops grown included above-ground (Swiss chard, *Beta vulgaris var cicla*; green pepper, *Capsicum annuum*; and green beans, *Phaseolus vulgaris*), below-ground (carrots, *Daucus carota*; beetroot, *Beta vulgaris*; and onions, *Allium cepa*) crops. These were selected on the basis of popular use and of the perceived risk of infection associated with crop consumption. Only the results for Swiss chard and carrot are presented here, since their growth was representative of the above-ground and below-ground crops, respectively.

Seedlings were obtained from a commercial nursery and planted in individual $20L$ polyethylene plastic bags filled with Berea red sand, with holes at the base for free drainage. The red colouration of Berea red sand is ascribed to the mineral haematite. Three experimental treatments were employed:

- Tap water
- Tap water enriched with nutrient medium (Chemicult)
- Greywater

The tap water treatment contained no additional nutrients and as such allowed comparison of concentrations in the greywater- and nutrient solution-treated soils to background concentrations. The contents of nutrient medium (Chemicult) are listed in Table 2.8:

Table 2.8: Contents of plant nutrient medium (Chemicult). Table is generated from [Rodda et al., 2011].

Chemicult Contents	**Amount (g/kg)**
NH_4^+	83
P	7
K	189
Mg	81
S	192
B	0.17
Fe	0.265
Mn	0.115
Zn	0.105
Cu	0.055
Mb	0.035

The plants were irrigated with their respective treatments two times per day in summer time and once a day in winter, with the exception of those receiving the nutrient solution. Nutrient solution was applied once a week and tap water was used on the remaining days.

2.9.1.3 Replication and Sampling

Plants were grown for a minimum of 12 weeks after planting the seedlings. Growth periods in winter were longer than in summer. The experiment was terminated after six crop cycles. To allow for accumulation of chemical constituents in the irrigation with greywater, the same soil was used throughout all crop cycles. At the end of each cycle, crops were harvested and 15 plants of each species per treatment were analyzed for macro and micronutrient content. Soil sampling was performed at the end of each growth cycle.

2.9.1.4 Greywater Characterization

Electrical conductivity (EC), Alkalinity, COD, ${NO_3}^{-}{-}N$, ${NO_2}^{-}{-}N$, ${PO_4}^{3-}{-}P$ and total Kjeldahl N, were analyzed according to standard methods (Standard Methods, 2005). Also, in order to measure the concentrations of Ca, Pb, Cl, Mg, Na, K, P, Zn, Cd, S, Fe and Mn, inductively coupled plasma atomic emission photometry (ICP-AES) was used. Table 2.9 contains the mean values of the chemical and microbiological analysis of tap water, greywater and nutrient solution. The mean pH of greywater was higher than that of either nutrient solution or tap water. Mean alkalinity, Cl, Na, total N, $PO_4{-}P$ and B levels were also markedly higher in greywater than in either tap water or nutrient solution.

2.9.2 Plant Growth Monitoring

Within a weekly time period, the growth of plants was evaluated, including plant height, fresh weight (whole plant; leaves for Swiss chard; root for carrot) and corresponding dry weight. Harvested crops at the end of each crop cycle were measured for fresh and dry weights for the determination of yield. Only dry weights are reported here.

2.9.2.1 Plant and Soil Nutrient Analysis

Vegetables were harvested after each crop cycle, and the total mean fresh weight was determined by summing the yields of individual crop type per treatments. At each harvest, the plants were completely removed (with roots) from the pots. The plant material was weighed, placed in paper bags and dried in an oven at $80°C$ for $72h$.

Table 2.9: Average concentrations (±standard error of mean) and the ranges of water constituents in greywater, nutrient solution and tap water. Table is adopted from [Rodda et al., 2011].

Variable	**Units**	**Tap water**	**Greywater**	**Nutrient solution**
Alkalinity	mg/L $CaCO_3$	29 ± 0.7	330 ± 58	66 ± 0.4
Boron	mg/L	< 0.25	3.4 ± 3.2	0.5 ± 0.3
COD		$-$	$280 - 310$	$-$
Calcium	mg/L	< 0.05	8.3 ± 1.7	< 0.5
Copper	mg/L	< 0.1	0.1 ± 0.1	< 0.1
EC		30 ± 0.1	267 ± 30	223 ± 15.6
Magnesium	mg/L	5.6 ± 0.8	7.5 ± 1.7	7.1 ± 0.3
$Nitrate + nitrite$	mg/L	0.91 ± 1.0	88 ± 1.1	1.2 ± 0.3
$Totalnitrogen$	mg/L	0.84 ± 0.3	206 ± 5.8	125 ± 0.1
$Ortho - phosphate$	mg/L	< 0.05	40 ± 7.0	38 ± 0.2
pH		$6.8 - 7.4$	$8.1 - 9.8$	$6.3 - 7.8$
Potassium	mg/L	3.1 ± 1.3	31 ± 2.7	7.1 ± 5.8
Sodium	mg/L	$-$	188 ± 27	32 ± 0.3
Sulphate	mg/L	0.05 ± 1.8	576 ± 27	137 ± 15.8
$TotalKjeldahlN$	mg/L	0.05 ± 0.1	206 ± 2.7	125 ± 15.2
$Totalphosphate$	mg/L	< 0.10	69 ± 0.6	49 ± 1.7
Zinc	mg/L	< 0.25	0.24 ± 0.4	< 0.10

They were analyzed for both macronutrients (N, P, Ca, K, and Mg) and micronutrients (Na, Zn, Cu, Mn, Fe, Al and B) by the Soil Fertility and Analytical Services Laboratory (KwaZulu-Natal Department of Agriculture and Environmental Affairs, Cedara, South Africa).

To analyze the subsamples of plant material, they were dried and burnt at $450°C$. The ash was dissolved in $1M$ HCl to determine the concentrations of different minerals.

The supernatant was analyzed for Al, Ca, Cu, K, Mg, Mn, Na and Zn by atomic absorption spectroscopy (AAS). Phosphorus concentrations were determined calorimetrically on a 2mL aliquot of filtrate using a modification of the Murphy and Riley molybdenum blue procedure. Potassium was determined from the extract directly on a flame photometer.

Soil sampling was carried out at the end of each crop cycle. Samples from a depth of $20cm$ were dried at room temperature and then crushed and sievedthrough a $1mm$ sieve. Analysis were performed for organic C, total C, N and S; and for extractable P, K, Zn, Mn and Cu.

The extraction solution contained $0.25M$ NH_4CO_3, $0.01M$ Na_2EDTA, $0.01M$ NH_4F and $0.05g/L$ Superfloc (N100), adjusted to pH 8. Phosphorus was determined on a $2mL$ aliquot of filtrate using the same molybdenum blue procedure as previously.

Potassium was determined on a $5mL$ aliquot of the filtrate after dilution with $20mL$ de-ionized water. Zn, Cu, Mn and Mg were determined by atomic absorption spectroscopy. Organic C in soil samples was determined by the Walkley-Black method, while total C, N and S were analyzed by the automated Dumas method using a LECO CNS 2000. The pH and EC were measured in water at a ratio of $1 : 2.5$. Note that analytical methods differed among sample types (greywater, plant material, soil) as determined by the nature of the sample and the standardized methods of the laboratory performing the analysis.

Chapter 3

Results of the Experiments

In chapter 2, several experiments have been reviewed, which had analyzed the application of greywater in the irrigation of different types of plants. They have analyzed mainly three parts of the plants: the edible parts under soil, the ones close to the soil and the ones above the soil. Besides, they also compared greywater irrigated plants with tap-water irrigated plants, being planted in same conditions.

In the following paragraphs, the results of the studied experiments are reviewed in order to identify the advantages and disadvantages of irrigation with different types of water, particularly the effects of irrigation with greywater.

3.1 Results of Crop Irrigation with Untreated Greywater

In Section 2.6, a brief description of the experiment by Finely et al. [Finley, 2008] about the effects of irrigating crops with greywater was done. In this section, the analyses of the experimental results are detailed.

3.1.1 Results and Discussion

3.1.1.1 Greywater Characteristics

The authors reported the characteristics of experimental greywater, which was similar to other studies (Table 3.1). Nutrients important for plant growth, namely N, P, and

K, were detected in minor quantities of $1.2 - 6.2$, $0.24 - 1.02$, and $2.2 - 2.5 mg/L$, respectively. Reasonably low P levels can be related to the use of phosphate-free soaps and detergents within the household. Greywater N, detected mainly as $NH_4^+{-}N$, was expected to be low due to the small absolute quantities of fecal matter present in greywater. Solids and COD levels of $313 - 543$ and $278 - 435 mg/L$ are indicative of a low-to-medium-grade wastewater [Jefferson et al., 2004]. Microminerals, such as calcium, magnesium, and sodium, were detected in quantities of $30 - 44$, $8.0 - 9.9$, and $20 - 27 mg/L$, respectively. Besides, sulfur was measured at levels of $5 - 8.8 mg/L$. There was no evidence of heavy metals in any detectable amount.

The presence of fecal coliform and fecal streptococcus varied weekly. Due to the presence of a young child, fecal bacteria counts were slightly higher than those previously reported [J. B. Rose, 1991].

Surprisingly, the untreated and treated greywater samples (GW_u and GW_t) were not significantly different for all measured parameters, indicating that the treatment was not effective to improve the quality of greywater.

3.1.1.2 Irrigation Effects

In terms of crop dry weight per experimental block, there is no significant difference between the irrigation with greywater and regular tap water. Authors justified the results by the low nutrient content of the greywater, and also low heavy metals. All plants grew well and produced healthy fruit, with only one lettuce control block suffering from pest-related weakness.

Fecal coliforms were detected in small numbers of lettuce leaves and carrot surfaces, but not at all on the surface of peppers. The highest fecal coliform counts were found on carrots, what is expected because the edible portion of the plant is exposed directly to the soil and irrigation water.

Fecal streptococcus colonies were found in a contrasting pattern relatively to that of fecal coliform. They were detected on all plant surfaces, with the highest contamination found on lettuce leaves. According to expectations, fecal streptococcus levels were higher on greywater irrigated lettuce and peppers, lower on carrots and lowest on the tap water-irrigated crops. The difference between treatments was not significant for any of the crops tested ($\alpha = 0.05$). Although water tests with KF streptococcus agar showed the growth of only one type of bacteria, food tests on the same media plates had a more varied appearance. Fecal coliforms were more likely to exist on carrots

Table 3.1: Greywater characteristics from various sources (Combined GW_u and GW_t results, NT not tested, ND none detected). Table is adopted from [Finley et al., 2008].

Parameter	**[Finley, 2008]**	**[Christova-Boal et al., 1996]**	**[Friedler, 2004]**	**[Surendran and Wheatley, 1998]**
pH	$6.7 - 7.9$	$6.4 - 10$	$7.4 - 7.5$	$7.6 - 8.1$
$TS(mg/L)$	$313 - 633$	NT	$1.090 - 2.021$	$631 - 658$
$COD(mg/L)$	$161 - 435$	NT	319-996	$424 - 725$
$NH_4^+ - N(mg/L)$	$1.2 - 6.2$	$< 0.1 - 15$	$1.2 - 4.9$	$1.56 - 10.7$
$P(mg/L)$	$0.24 - 1.21$	$0.062 - 42$	$3.3 - 55.0$	$1.63 - 101$
$K(mg/L)$	$0.6 - 4.4$	NT	NT	NT
$Al(mg/L)$	ND	$< 1.0 - 21$	NT	NT
$Ca(mg/L)$	$28 - 44$	3.5-12	NT	NT
$Cd(mg/L)$	ND	< 0.001	NT	< 0.001
$Co(mg/L)$	ND	NT	NT	NT
$Cr(mg/L)$	ND	NT	NT	NT
$Cu(mg/L)$	ND	$< 0.05 - 0.27$	NT	$0.11 - 0.32$
$Mg(mg/L)$	$8.0 - 10.1$	$1.1 - 2.9$	NT	NT
$Mn(mg/L)$	ND	NT	NT	NT
$Mo(mg/L)$	ND	NT	NT	NT
$Na(mg/L)$	$18 - 27$	$7.4 - 480$	$151 - 530$	NT
$Pb(mg/L)$	ND	NT	NT	$0.003 - 0.03$
$S(mg/L)$	$3.3 - 8.8$	$1.2 - 40$	NT	NT
$Fe(mg/L)$	$0.1 - 0.45$	$0.29 - 1.1$	NT	NT
$Zn(mg/L)$	$0.01 - 0.42$	$0.09 - 6.3$	NT	$0.059 - 0.31$
SAR	$3.9 - 6.1$	NT	NT	NT
Fecal coliform (*cfu/100mL*)	$2.2 \times 10^4 - 1.4 \times 10^6$	$110 - 3.3 \times 10^3$	4×10^6	$600 - 728$
Fecal streptococci (*cfu/100mL*)	$1.13 - 8.10$	$23 - 2.4 \times 10^3$	NT	NT

and fecal streptococci were more likely to be present on lettuce.

The low levels of indicator bacteria found on the food crops, regardless of the high numbers in greywater samples, may indicate some buffering effect of the soil biotic community, or signal the unfitness of the chosen indicator bacteria to indicate crop contamination by aquatic pathogens. The movement of each pathogenic organism on plant surfaces and into plant tissues will naturally be species-specific and may be difficult to predict with the employed methodology.

The relative absence of fecal streptococci bacteria from carrot surfaces and their prevalence on above ground crops is indeed noteworthy, as it runs contrary to conventional logic concerning crop contamination. This may indicate some degree of contamination of above ground plants by airborne streptococci from other sources or the movement of bacteria from the soil to the crevice-filled leaves of young lettuce plants. Fecal coliform results more closely mirror expectations for bacterial transmission by contaminated irrigation water. Furthermore, this group encompasses the *E. coli* species, some strains of which are foodborne pathogens known to be responsible for outbreaks of illness in humans. For these reasons, fecal coliforms, or more specifically, *E. coli*, may be more appropriate for use as indicator organism in future research. Confirmation of the appropriateness of the indicators is important to efficiently investigate the real risk associated with irrigating food crops with fecal contaminated waters of all types.

The high variation of bacterial results in this study echoes previous researches, where other greywater flows [Jackson et al., 2006], sludge applications [Ibiebele and Inyang, 1986], and full wastewater [Sadovski et al., 1978] were not found to increase crop contamination when contact was avoided. This is significant because it opens the door for the exploration of alternative requirements for non-potable sources of irrigation water. More factors need to be investigated, including bacterial survival and accumulation in the soil, transmission of viruses and parasites, and survival of organisms into drainage or groundwater, to fully investigate the use of domestic greywater for irrigation purposes.

3.1.1.3 Risk analysis

Regardless of the lack of published microbiological standards for fresh products, the real risk associated with the consumption of crops irrigated with greywater is difficult to evaluate. In its 1986 publication, the International Commission on Microbiological Specifications for Foods suggested a limit of $100 cfu/g$ for *E. coli* on fruits and vegetables, with a sample size (n) of at least five (5) and with no more than two (2) samples exceeding that limit in any testing period. Since *E. coli* is incorporated into the fecal coliform category, this risk analysis can be translated into a conservative limit of $100 cfu/g$ for fecal coliforms. Crop results from this study did not exceed this level, nor was any one sample found to exceed it.

While there is no conventional standard for Enterococci levels on foods, the real danger of their presence is not clear. Fecal streptococci naturally occur in some foods, most notably meats and cheeses, and their relationship to other pathogenic organisms in that setting is unclear [Franz et al., 1999].

Data for the probability of infection and likeliness of illness per incidence of infection are based on Hurst [Hurst et al., 2002], who provides overall values for enteric pathogenic bacteria. It is assumed that the risk analysis is performed in the situation where the vegetable crops are consumed at an estimated rate of one $40g$ serving/day (approximately one pepper, three carrots, or six lettuce leaves), every other day, over a 3-month harvest period.

3.2 Results of Irrigation with Treated Greywater

In section 2.7, the experiment performed by Al-Hamaiedeh and Bino, 2010 was briefly presented [Al-Hamaiedeh and Bino, 2010]. In this section, the results from their experiment are discussed to identify the advantages and disadvantages of treating greywater concerning the growth of plants and the fertility of soil.

3.2.1 Results and Discussion

The estimated average greywater generation rate was 30 $\pm 3.6 L/c.d$. The low water consumption rate in the study area (compared to European communities where it ranges between 66 and $274 L/c.d$) was responsible for producing greywater characterized by high BOD, COD, and TSS values (Table 3.2). The average BOD, COD and TSS concentrations for the effluent at As-Samra Waste Stabilization Ponds are $709 mg/L$, $1868 mg/L$ and $559 mg/L$ respectively [Fittschen and Niemczynowicz, 1997]. COD values were reported to vary for raw greywater between sites from 92 to $2263 mg/L$, with similar variations arising at an individual site, due to changes in the quantity and type of detergent products employed.

Table 3.2: Quality of raw and treated greywater compared with allowable limit for restricted irrigation ($\bar{x}$ and SD represent average and standard deviation respectively). Table is adopted from [Al-Hamaiedeh and Bino, 2010].

Parameter	**Raw GW**			**Treated GW**			**Allowable limit**
	Range	$\bar{x}$	SD	Range	$\bar{x}$	SD	
pH	6.9 – 7.8	7.2	0.25	6.8 – 7.9	7.2	0.23	6 – 9
TSS (mg/L)	23 – 358	275	80.1	12 – 312	128	25.1	150
BOD (mg/L)	110 – 1240	942	244.5	10 – 412	108	68	200
COD (mg/L)	92 – 2263	1712	592.5	36 – 763	489	124.3	500
EC (ds/m)	1.57 – 2.0	1.83	0.11	1.46 – 1.91	1.76	0.18	> 2
Nitrate (mg/L)	0.44 – 0.93	0.68	0.62	< 0.2	–	–	40
Total N (mg/L)	38 – 61	52	–	8 – 14	11	2.6	70
Cd (mg/L)	–	0.008	–	–	0.008	–	0.01
Pb (mg/L)	1.0 – 1.31	1.19	0.11	0.8 – 1.15	1.13	0.10	5
SAR	2.23 – 4.76	3.3	0.8	1.8 – 3.6	2.8	0.6	9

The average COD removal efficiency (72%) achieved in both 4-barrel and CT treatment units is reported to be satisfactory, comparing to those reported for popular on-site wastewater treatment methods [Al-Hamaiedeh and Bino, 2010]. The average COD removal efficiencies for septic tank followed by intermittent sand filter are also reported in Table 3.3.

Table 3.3: The long-term impact of greywater irrigation on soil EC, SAR and organic matter (OM) content. Table is adopted from [Al-Hamaiedeh and Bino, 2010].

Soil Depth (cm)	**Parameters**	**Sampling Period**		
		Before GW Irrigation	**2006**	**2007**
$0-30$	**SAR**	1.42 ± 0.62	1.49 ± 0.5	3.84 ± 1.83
	EC (ds/m)	0.53 ± 0.14	1.55 ± 0.44	1.83 ± 0.87
	OM (%)	2.83 ± 1.15	3.99 ± 0.64	0.81 ± 0.18
$30-60$	**SAR**	1.88 ± 0.83	2.15 ± 0.6	4.00 ± 2.09
	EC (ds/m)	0.63 ± 0.22	1.55 ± 0.44	2.27 ± 1.85
	OM (%)	2.83 ± 1.15	3.89 ± 1.09	0.88 ± 0.24

Soil properties, mainly salinity, SAR, and organic content, are important for plant health and growth. The average SAR value of treated greywater in this study was 3.62 which is less than the values suggested in literature [Al-Hamaiedeh and Bino, 2010] and the allowable limit presented in Jordanian standards (Table 3.2). Therefore, authors concluded that the proposed method provided a suitable framework for irrigation with treated greywater. The average salinity value of treated greywater was $1.76 dS/m$ which is lower than the $2 dS/m$ stated in Jordanian standards. Since the toilet flow was excluded in the beginning of the experiment, the detergents and soaps are more concentrated in greywater. The introduction of particulate and organic matter such as surfactants can alter soil permeability [Al-Hamaiedeh and Bino, 2010].

Beside the experiment, the authors also studied long-term effects of greywater reuse on soil properties during the period extending from 2006 to 2007. The results showed a gradual increase of salinity and SAR with time (Table 3.3). This increase might be explained by the following reasons: high evaporation rates, low rainfall and absence of drainage system. Due to low rainfall in 2007, households in the study area used tap water for irrigation. Irrigation with tap water caused soil leaching which reduced organic content of the soil.

No evidence of chemical impact on leaves and fruits of olive and crops, due to irrigation

Table 3.4: Concentration of selected minerals and metals in olive leaves and fruits. Table is adopted from [Al-Hamaiedeh and Bino, 2010].

Parameters	**Olive trees irrigated with GW**		**Olive trees irrigated without GW**	
	Leaves	**Fruits**	**Leaves**	**Fruits**
Pb (mg/L)	< 0.01	< 0.01	< 0.01	< 0.01
Cd (mg/L)	< 0.002	< 0.002	< 0.002	< 0.002
N (%)	1.75 ± 0.36	0.52 ± 0.21	1.66 ± 0.53	0.34 ± 0.26
P (%)	0.14 ± 0.05	0.08 ± 0.02	0.12 ± 0.04	0.07 ± 0.03
K (%)	0.71 ± 0.23	1.72 ± 0.42	0.79 ± 0.21	1.34 ± 0.57
Na (%)	0.03 ± 0.02	0.09 ± 0.02	0.06 ± 0.03	0.03 ± 0.01
Cl (%)	0.21 ± 0.04	0.22 ± 0.04	0.22 ± 0.03	0.21 ± 0.04

with greywater, was reported (Table 3.4). This makes the reuse of treated greywater for olive trees irrigation a high potential solution for the study area.

Considering heavy metals such as cadmium and lead, measurements show almost no increase in the uptake by plants, since their concentration was low in treated greywater and soil. However, long-term use of reclaimed water can lead to salt and metal accumulation in the soil and subsequent uptake by the plants [Al-Hamaiedeh and Bino, 2010]. The chemical properties of vegetable crops irrigated with greywater (Table 3.5), did not differ from the properties of the same crops irrigated with fresh water.

3.3 Evaluation of Passive Irrigation with Greywater

In this section, the results from the investigation by Fagan [Fagan, 2015] are discussed. The research aimed to evaluate the possibility of using greywater as an alternative to freshwater for irrigating crops. The experimental approach was presented in section 2.8, so in here we discuss the details and measurements.

Table 3.5: Concentration of selected chemical parameters in crop leaves and fruits. Table is adopted from [Al-Hamaiedeh and Bino, 2010].

Plant		**N (%)**	**P (%)**	**K (%)**	**Na (%)**	**Cl (%)**	**Pb (*ppm*)**
Okra	**Fruit**	2.62 ±1.2	0.36 ±0.11	2.55 ±1.12	0.07 ±0.02	0.84 ±0.2	0.41 ±0.18
	Leaves	2.67 ±0.9	0.23 ±0.13	2.23 ±0.93	0.05 ±0.01	0.86 ±0.19	0.90 ±0.14
Bean	**Fruit**	2.52 ±0.8	0.43 ±0.18	2.97 ±0.78	0.04 ±0.02	0.97 ±0.26	ND
	Leaves	3.06 ±0.5	0.50 ±0.13	2.63 ±0.91	0.06 ±0.02	1.97 ±0.66	0.48 ±0.19
Corn	**Fruit**	2.03 ±0.6	0.31 ±0.09	1.0 ±0.24	0.03 ±0.01	0.21 ±0.08	0.95 ±0.2
	Leaves	1.93 ±0.7	0.37 ±0.14	1.91 ±0.47	0.06 ±0.02	0.83 ±0.26	0.49 ±0.21
Sunflower	**Fruit**	2.01 ±0.5	0.23 ±0.08	1.92 ±0.64	0.03 ±0.02	0.20 ±0.07	0.49 ±0.2
	Leaves	3.17 ±1.2	0.38 ±0.12	3.03 ±1.32	0.06 ±0.03	1.11 ±0.43	0.46 ±0.17

3.3.1 Results and Discussion

Height and leaf count were measured throughout the two-month growth process. At the end of the growth process, root lengths, root mass, total fresh mass and total dry mass were measured. These measurements were then analyzed to determine how the different watering variables affected plant growth.

The experiment revealed that the plants irrigated with greywater have grown faster, while the plants that had been received high volumes of freshwater grow less than the others. Figure 3.1 presents the average growth rate of the plants which reached full-grown height. The full-grown plants irrigated with high volumes of greywater grew slightly faster than the plants irrigated with high volumes of freshwater. To complete the test, two tailed t-tests for paired samples were calculated to look for significant differences in the final height and the final leaf counts. The full grown plants final heights for both the greywater irrigated plants and freshwater high-volume irrigated plants were significantly greater ($p < 0.05$) than the ones of freshwater irrigated plants. However, the greywater irrigated plant heights were not significantly different from the heights of the freshwater high-volume irrigated plants.

Measurements taken after the plants were harvested are shown in Figure 3.2. Fig-

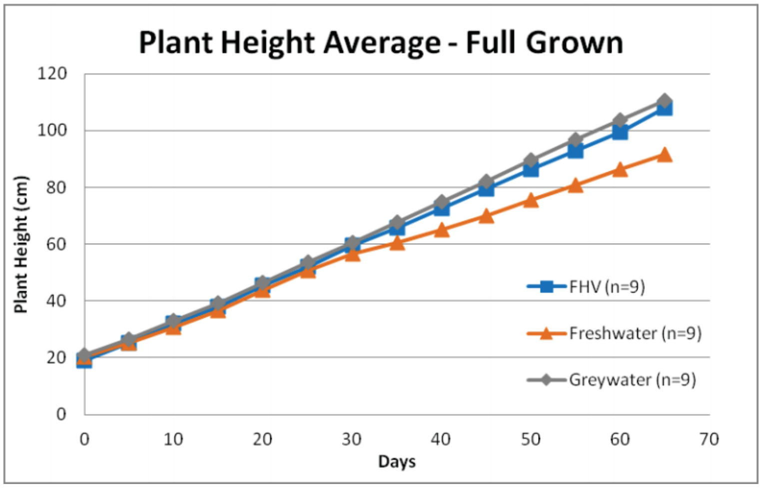

Figure 3.1: Average growth rate of plants reaching full grown height. Figure is adopted from [Fagan, 2015].

ure 3.2-a shows the average length of the longest root of full-grown plants. Both groups irrigated with freshwater developed longer roots than the the group irrigated with greywater. The plants irrigated with high volumes of freshwater grew the longest roots. Figure 3.2-b shows that the plants irrigated with low volumes of freshwater developed a greater root mass than the other groups. This indicates these plants had to divert more energy growing roots to seek out the less available water. An extensive root system is important for the health of the plant, allowing it to anchor more securely in the soil and to tolerate fluctuations in watering [Fagan, 2015].

The root measurements for the seedlings in Figure 3.2-c show that the greywater irrigated plants had, on average, a slightly longer root than the other plants, but distinctly outpaced the other plants in root mass. As the greywater encouraged these young plants to establish a stronger root system early in development, they will most likely be healthier through maturation.

Unfortunately, only a few of the plants produced flowers and none produced tomatoes to be able to test for high levels of contaminants. In general, the plants irrigated with greywater grew faster, produced more leaves, and had more biomass than the other plants.

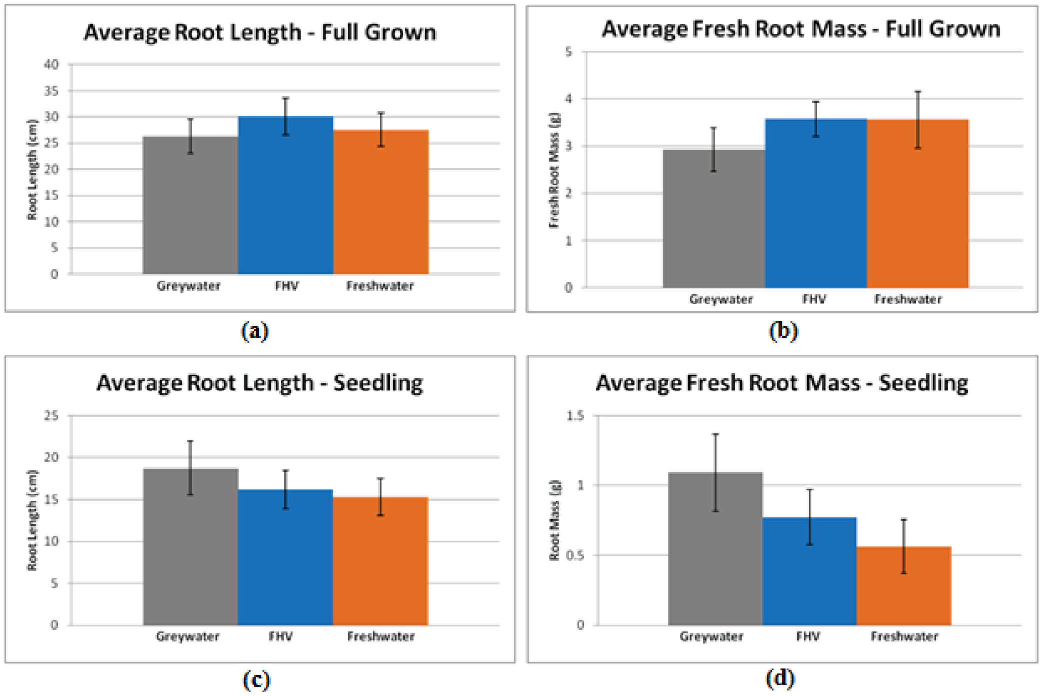

Figure 3.2: a. Average root length of a full grown crop; b. Average fresh root mass of a full grown crop; c. Average root length seedlings; d. Average fresh root mass seedlings. All the figure are adopted from [Fagan, 2015].

3.3.2 Risk factors

Fagan stated the possibility of risk, when watering in large volumes, that a plant will not establish a strong root system. However, the mature plants under high volume irrigation were able to grow similar root masses when compared to the plants under low volume irrigation. This indicates that the high volume irrigation plants were able to withstand winds and changes in watering. Because the greywater seedlings were able to grow larger root systems, they would most likely be more stable as they mature, and able to divert more energy to leaf, flower and fruit production.

The same author identifies another risk of greywater irrigation is that high amounts of nutrients can damage young plants. However, as indicated by Figure 3.3, the seedling growth and root development were not hindered. Overall, the results of this study, though limited in scope, indicate that simple greywater irrigation systems, like those established during the project in Chirifoyilli in Ghana, as well as those already in place in other villages, serve as a valuable source of nutrients and water, and will likely not harm plants.

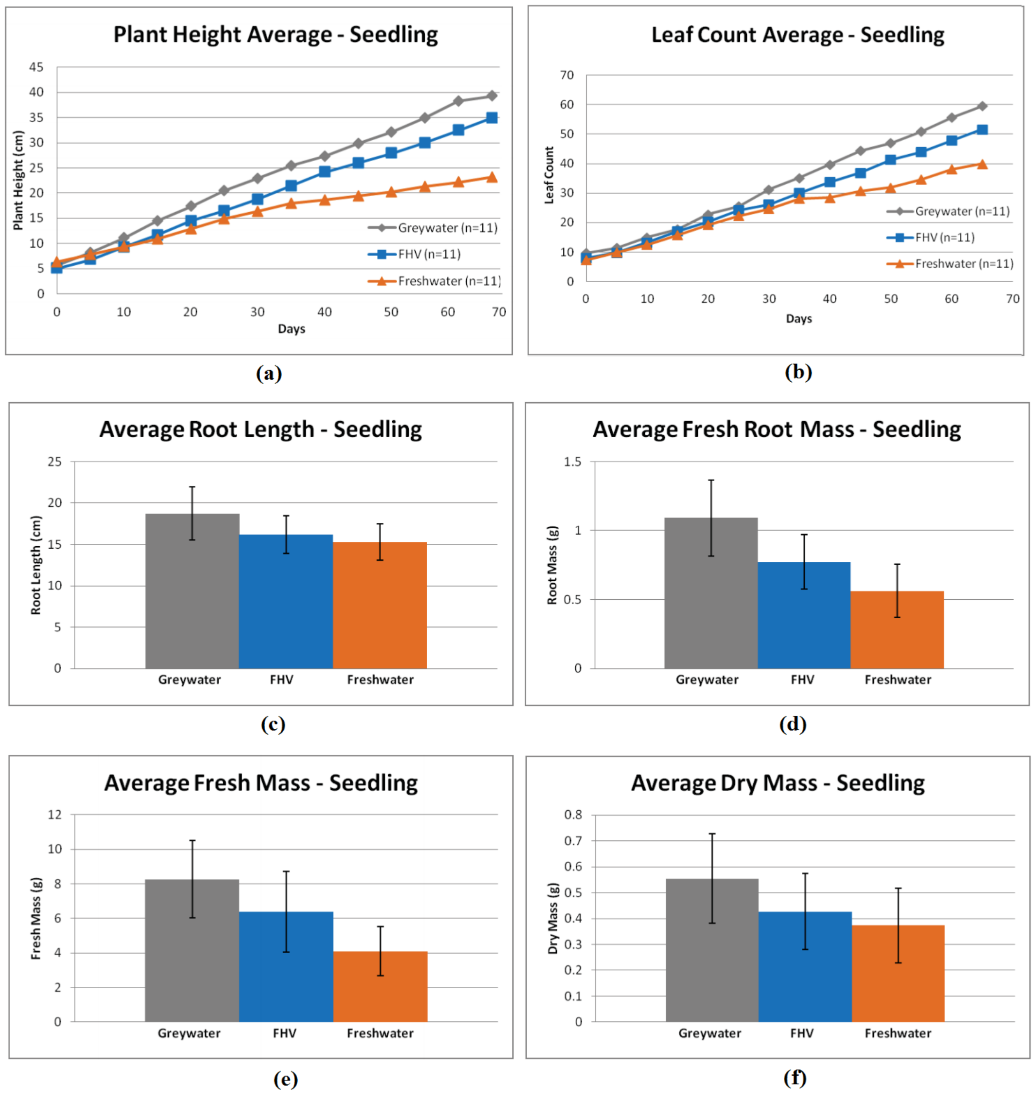

Figure 3.3: a. Average Growth rate of seedlings classified by watering variable; b. Average leaf count of seedlings classified by watering variable; c. Average final root length of seedlings; d. Average final fresh root mass of seedlings; e. Average final fresh mass of seedlings; f. Average final dry mass of seedlings. all the figure are adopted from [Fagan, 2015].

3.4 Results of Irrigation with Domestic Greywater

In section 2.9, a brief description of the experiment by Rodda et al. [Rodda et al., 2011] was carried out. They performed an experiment to evaluate the application of greywater in small scale crop fields. To do that, they irrigated two types of plants with three sources of water. In this section, the results obtained with their experience are presented and discussed.

3.4.1 Results of the Experiment

3.4.1.1 Plant Growth

Swiss chard The results indicate that nutrient solution and greywater increase the growth of Swiss chard when compared to irrigation with tap water. The growth of plants irrigated with greywater was reported to improve from the first growth cycle to the second, and declined thereafter. Growth had declined noticeably by the sixth cycle.

Carrot As seen for Swiss chard, nutrient solution and greywater yielded similar heights for the above ground plant parts, which were significantly greater than those obtained with tap water. As it was expected, the plant heights for all treatments decreased from the second cycle onwards. Similarly, by the fifth and sixth crop cycles, plant height had decreased significantly for all treatments.

3.4.1.2 Crop yield

Swiss Chard The results indicate that the nutrient solution irrigated Swiss chard showed significantly greater yield than greywater and tap water-irrigated Swiss chard. Surprisingly, yield was consistently lower for greywater irrigated plants than for those irrigated with nutrient solution. However, it should be noted that previously it was reported that the plant height irrigated with greywater was higher than the other ones. Consistently, there was a remarkable decrease in the yields after the second crop cycle. On the other hand, yield from tap water irrigated plants was extremely low for all crop cycles.

Carrot Yield was significantly greater for plants irrigated with nutrient solution than the yield for greywater irrigated plants. The yield from plants irrigated with tap water was minimal. Yield of all treatments declined steadily over time.

3.4.1.3 Macronutrient concentrations in crops

Swiss chard Researchers reported that irrigation with either nutrient solution or greywater resulted in significantly higher concentrations of the macronutrients N, P, K, Ca, Mg and S in Swiss chard leaf tissue. Concentrations of P increased with consecutive crop cycles in Swiss chard plants irrigated with nutrient solution and greywater; however, Ca was reported to decrease from the second crop cycle onwards. The other micronutrients did not show a consistent trend over successive crop cycles.

Carrot Although Swiss chard is an above-ground leafy crop and carrots are a root crop, the changes in the concentrations of macronutrient in carrot crops over five crop cycles followed the same trend as the observations for Swiss chard.

3.4.1.4 Micronutrient concentrations in crops

Swiss chard Leaves of Swiss chard plants irrigated with greywater and with nutrient solution contained similar mean concentrations of the micronutrients Zn, Cu, Mn, Fe, Al and B $\cdot$ All levels were significantly higher than in plants irrigated with tap water. Na was mostly present in higher levels in leaves of plants irrigated with greywater. Mean Na levels in plants irrigated with greywater and with nutrient solution increased during the crop cycles. The average levels of Zn, Cu and Mn also increased with successive crop cycles in plants irrigated with nutrient solution and greywater. Besides the increase in some micronutrients, some others such as Fe, Al and B showed no consistent trend regarding the crop cycles.

Carrot Carrots from plants irrigated with nutrient solution and with greywater always had significantly higher mean levels of all measured micronutrients than did carrots from plants irrigated with tap water. Mean levels of Cu, Mn and B were similar in carrots from plants irrigated with nutrient solution and greywater. The results show that levels of Na, Zn, Fe and Al were significantly higher in plants irrigated with greywater. The level of Na, Zn, Fe and Al increased in crops irrigated with greywater. Therefore, the authors concluded that both above-ground and root crops showed a tendency to accumulate Na and metals.

3.4.2 Conclusion of Experiment

The result of this experiment revealed that irrigation with greywater increased plant growth and crop yield. Also, greywater irrigation was associated with improved plant nutrient content. However, greywater irrigation leads to accumulation of salts and metals in soil with time, and hence to the accumulation of sodium and metals in plants, which is not appropriate for soil health in the long time.

Chapter 4

Effects of Greywater Irrigation

Several studies have shown further advantages can be gained by the usage of greywater as it has different impacts on the quality of crops. Besides, it affects the soil, not only in short-time usage, but also in long-time usages. Various researches have been done to determine the effects of greywater irrigation, however, different outcomes have been achieved. Some studies reported that greywater irrigation of crops can increase plant growth [Day et al., 1981] [Rusan et al., 2007] and crop yield [Salukazana et al., 2005] [Misra et al., 2009] without any impacts on the quality of the crop [Day et al., 1981] [Zavadil, 2009]. On the other hand, it was reported in [Al-Zubi and Al-Mohamadi, 2008] that there are various types of crops which have been shown to have the same yields when greywater is used to irrigate them.

4.1 Effects of Greywater Irrigation on Crops

The application of greywater for garden irrigation is not recommended in some cases [Ng, 2004]. Greywater is typically made up of chemicals such as boron, sodium, other salts, chlorine and alkaline chemicals. Some of these chemicals can be harmful to vegetation or soils if the greywater is used for irrigation of garden [Jeppesen and Solley, 1994].

Boron is found in many detergents and cleansers. While it is beneficial in small concentrations, it is toxic to animals in high concentrations [Prillwitz and Farwell, 1995]. US Environmental Protection Agency recommends that the maximum concentration of boron, for long term exposure, should not exceed $0.75g/L$ [Ng, 2004].

Excessive sodium results, not only in poor soil structures, but also in decreased drainage capacity [Jeppesen and Solley, 1994]. Besides, high levels of sodium can also be detrimental to the growth of some plants. Sodium will be massively contributed by detergents as long as sodium salts are used in laundry powder as a filler [Patterson, 2000b] [Prillwitz and Farwell, 1995].

The pH of greywater typically ranges between 6.5 and 9.0. An increased use of soaps by inhabitants may increase the pH. Therefore, long-term irrigation may turn soils progressively more alkaline [Ng, 2004].

The irrigation of plants must also be carried out with caution as greywater is relatively high in nutrient content; however, there are some plants which are less tolerant to phosphorus excess [Jeppesen and Solley, 1994] [Ng, 2004]. For example, plants of the *Proteaceae* family, such as *grevillea*, *hakea*, *banksia* and silky oak, are vulnerable to excess phosphates.

The phosphorus content in various detergents can range from 0.05% up to 10%. Results from the study of Patterson showed that the actual phosphorus contents in laundry products ranges from approximately $1mg/L$ to approximately $54mg/L$ in a full wash load. For example, a phosphorus content of $7.8g$ per wash is equivalent to a concentration of $50mg/L$ in a full wash load [Patterson, 2000a].

4.1.1 Plant Growth

Greywater can reduce plant growth due to excessive levels of toxic elements such as boron (B), chlorides (Cl^{-1}), and cadmium (Cd) [Mzini, 2013]. Also long time usage can impact the quality of the soil, by causing soil pore clogging due to grease, phosphates (${PO_4}^{3-}$) and sodium (Na) [Ayers and Westcot, 1994]. These plant nutrients are essential for plant growth but are required in relatively small concentrations [Rusan et al., 2007]. In addition, Omami [Omami, 2005] found that salinity affected plant growth in a number of ways: reduced infiltration; deterioration of the physical structure of the soil, which in turn diminishes permeability and soil aeration; and caused an increase in the concentration of certain ions which have an inhibitory effect on plant metabolism. The general response of plants to soil salinity is known to reduce plant growth such as germination [Omami, 2005], root and shoot length, and overall dry mass [Agarwal and Pandey, 2004], and leaf necrosis [Wahome et al., 2001].

Studies suggest that caution should be taken when sensitive crops such as pepper, potato and corn are irrigated with greywater from a source whith a high salt concentration. Leaf damage and crop failure can be due to the presence of high levels of salt concentration [Ayers and Westcot, 1994] [Bauder et al., 2007]. It has been recommended to perform the irrigation of crops with highly concentrated greywater by dripping and surface irrigation, since it allows water to spread next to the plant root without direct contact with the leaves [Al-Jayyousi, 2004] [Holtzhausen, 2005]. However, salt and boron tolerant plants, such as olives, sugar beet and tomato, will not present any problem when they are irrigated with greywater [Bino, 2003] [Bauder et al., 2007].

Day et al. [Day et al., 1981] found that irrigation with diluted municipal greywater (rate of 1 : 1) will produce taller cotton plants with more vegetative growth when compared with the use of potable water. Also, a similar study by Rusan et al., [Rusan et al., 2007] proved Day's experiment, showing that the addition of essential nutrients such as N, P, and K will result in higher plant biomass in the production of barley.

However, several observations by different studies have shown that no significant difference was measured on plant growth parameters. For example, biomass of lettuce and carrots [Finley et al., 2008]; and tomatoes [Misra et al., 2009] was not significantly different when irrigated with greywater compared to potable water. In another research carried out in 2008, silverbeet irrigated with 100% greywater presented a slight reduction in shoot and root biomass when compared to other treatments (greywater diluted with potable water at 1 : 1 ratio and 100% potable water) [U. Pinto, 2010].

In conclusion, it was understood from the literature that crops such as lettuce have no significant response to the nutrients of greywater; however, pepper, potato and corn are more sensitive to the changes of elements such as Na in the soil and tend to have less growth. On the other hand, cotton and barley showed significant growth when they were irrigated with greywater compared to tap water. Therefore, plant growth in response to greywater irrigation appears to depend not only on the type of crop, but also on the nutrient content of the irrigation water.

4.1.2 Crop Yield

The research from Day et al. [Day et al., 1981] showed that the application of greywater in agriculture can increase crop yield, since it contains finite concentrations of essential macronutrients such as N and P [Day et al., 1981]. Cotton yield was improved by using diluted municipal wastewater with groundwater at 150 : 1 mixture when compared to groundwater alone from wells in Arizona [Day et al., 1981]. Similar results have been claimed in an experiment carried out by Rusan [Rusan et al., 2007]. Tomatoes irrigated with greywater obtained higher nutrient uptake and biomass at the flowering stage when compared to tap water [Misra et al., 2009].

Despite the significant increase of the yields, some researchers have reported that irrigation with greywater had no significant impacts on crop yields. In the case of a study in Jordan, where tomatoes were irrigated with greywater, there was no increase in yield compared to those irrigated with potable water [Al-Zubi and Al-Mohamadi, 2008].

No study has reported the reduction of crop yield regarding irrigation with greywater. Nevertheless, it should be noted that water containing 1% of NaCl was observed to reduce yields of lettuce, endive and fennel significantly [Pascale and Barbeieri, 1995].

4.1.3 Crop Quality

The quality of irrigation water impacts crop yield, and both internal and external qualities of the product [Zavadil, 2009]. Consumer satisfaction is based solely on subjective observation and further evaluation, including the color and firmness of product [Shewfelt, 1999]. According to the study by Wagner [Wagner et al., 1998], vegetables quality can be ranked by a simply scoring system on a 1 to 5 scale (poor to excellent) by subjectively regarding the size, uniformity and defects. For instance, a good quality cabbage head should be fresh, hard, fully developed with an average head size [Wagner et al., 1998].

Research on the external quality of crops regarding greywater irrigation has not shown an equal trend. Zavadil [Zavadil, 2009] reported that the usage of wastewater did not improve crop quality of sugar beet and starch in potatoes. Similarly, Day et al., [Day et al., 1981] observed no significant improvement in the quality of the cotton lint while irrigating either with greywater or with groundwater. Most of the research in greywater irrigation focuses on nutrients that affect the chemical properties of crops. For instance, Rusan et al. [Rusan et al., 2007] found that after a period of 10 years of irrigation with wastewater, the content of Pb and Cd of barley crops increased to the maximum recommended level. Similarly, their measurement of Ni and Pb on wheat showed average concentrations of $23.39 mg/kg$ and $25.40 mg/kg$ which are higher than acceptable recommendations. Also, Cd measured on spinach and lettuce was found to be eight times more than FAO/WHO permissible levels ($0.2 mg/kg$) [Qishlaqi et al., 2008]. That's a situation in which exposure to low levels of $2 - 3 \nu g$ Cd may result to kidney damage, bone defects and fractures [Jarup, 2003]. The presence of Zn, or the application of lime or gypsum in the soil, guarantees a limit to the uptake of Cd by plants [Wahlquist, 2009].

The availability of micronutrients such as Zn and Fe in food is reported to be vital for consumers' health [White and Broadley, 2005]. Although Zn is nutritious to humans, a maximum tolerance of $20mg/kg$ has been regulated for crops [Long et al., 2003]. Therefore, crops with a maximum content of $5mg/kg$ of Zn and Fe are considered to have a better nutritional quality than those with less [Worthington, 2001]. Some crops have the potential to maintain the same levels of nutritious elements, such as Fe and Zn, when they are irrigated with either greywater or potable water. For instance, lettuce and spinach are reported to have such behavior [Rodda et al., 2011]. However, barley showed a different trend, since both Fe and Zn were higher with greywater irrigation during the experiment done by Rusan [Rusan et al., 2007].

In theory, increasing the levels of Na in crops, will lead to a reduction in the plant quality and productivity [Jacobs and Staden, 2008]. The study to evaluate the level of sodium was done by Zavadil [Zavadil, 2009]. There was a significantly higher Na content in sugar beet and potato when irrigated with treated municipal wastewater. The researcher did not report any physiological consequences of sodium accumulation in the studied plants. However, high Na concentrations may lead to leaf chlorosis (brown patches on the leaf tips) on lettuce, as observed by Weil-Shafran et al. [Weil-Shafran et al., 2006]. They showed that higher levels of Na uptake by the plants decreases osmotic potential, which will lead to reduced plant water uptake; thus, plant total moisture content drops down significantly [Barker-Reid et al., 2010]. In a study by Holtzhausen [Holtzhausen, 2005], tomatoes irrigated with greywater were reported to have higher Na contents when compared to those irrigated with tap water. Caution should be taken since water containing approximately 1% of NaCl was found to significantly reduce the moisture and dry the content of lettuce, which reduced the market value of the crop [Pascale and Barbeieri, 1995].

As a conclusion, it can be said that choosing greywater as an alternative irrigation method should be taken into consideration together with the type of crops; for instance, lettuce has a good potential to be irrigated with greywater since better crop quality will be obtained.

4.2 Effects of Greywater Irrigation on Soil

Greywater has both negative and positive environmental effects on soil. Depending on the type of greywater application, there have been different studies trying to understand the impacts of greywater irrigation.

In rural areas, greywater is disposed directly on the ground, near dwelling places, and often results in several hazards. Concerning the environmental hazards, they can be named as pollution of wetlands, underground water supply and infiltration of salts, oils and grease into the soil [Vuuren, 2007]. Additionally, it has been reported by Rusan that the organic matter in greywater is likely to build up organic matter in the soil [Rusan et al., 2007].

As shown in Table 4.1, oil and grease from the kitchen sink are found in greywater and accumulate up to approximately $200 mg/kg$ in the soil, due to the irrigation of crops; and effectively reduce the infiltration rate of the soil [Travis et al., 2008]; however, different sources of untreated greywater determine the type of effects on the soil.

Table 4.1: Effects of domestic greywater on soils. Table is generated based on [Travis et al., 2008], [Misra et al., 2009], and [Holgate et al., 2011]

Greywater source	**Pollutants**	**Effects on the soil**	**Reference**
Kitchen sink	Grease and oil	Reduction in soil water capillary rise	[Travis et al., 2008]
Washing machine	Surfactants and salts	Modest influence on soil water retention and evapotranspiration	[Misra et al., 2009]
Bath tub	Micro-organisms, such as *E. Coli*	High electrical Conductivity (EC)	[Holgate et al., 2011]

As can be seen in Table 4.1, greywater from a bath tub is reported to have less pollutants comparing to other forms of domestic greywater [Jefferson et al., 2004], however this water, due to high Na^+ ion concentration, induces a high electrical conductivity on soils if it is used for irrigation [Holgate et al., 2011]. The presence of Na^+, not only increases the salinity of soil, but also increases its electrical conductivity, which can result in low soil productivity [Rusan et al., 2007].

Chemical concentrations of vegetables irrigated with greywater show different trends. For example, cabbages, onions, lettuce and carrots irrigated with greywater, contain higher concentrations of Na^+ whereas beetroot and spinach do not show any effect of

Na^+. However, nutritional elements such as Zn^{2+} and Fe^{2+} were significantly raised in vegetable crops, namely cabbage, onions and spinach irrigated with diluted greywater [Mzini, 2013].

Long term irrigation with sewage and greywater affects not only the soil, but also underground sources. A study conducted by Farid [Farid et al., 1993] showed that Egypt underground water was contaminated by nitrogen, phosphate, heavy metals and fecal *E. coli* because of irrigation with sewage effluent for 75 years [Farid et al., 1993]. Another long term study, by Rusan et al. [Rusan et al., 2007], revealed that there was an increase in salts, organic matter, and plant nutrients in the soil following greywater irrigation in a 10-year period. The evaluation of the presence of heavy metals in the soil lead to different conclusions. Rusan et al. [Rusan et al., 2007] reported that there was no increase in heavy metals in the soil. However, Bolivian researchers Al-Zu'bi and Al-Mohamadi [Al-Zubi and Al-Mohamadi, 2008] reported an increase in heavy metal concentrations for Cd and Ni compared to concentrations before irrigation, although they mentioned the concentration of heavy metals was lower than standards. In order to normalize the concentration of some heavy metals in the soil, plants can be used. Misra et al. [Misra et al., 2009] claimed that tomato plants irrigated with greywater removed about 86% more of additional Fe from the soil when irrigation is carried out with greywater.

Since the accumulation of salt can occur in both fertilized water and greywater irrigated plots, Gross et al. [Gross et al., 2005] proved that no risk of salinity was detected in a 3-year period. They showed that long-term use of greywater on fields may not necessarily pollute the underground water [Duttle, 1996].

There have been reports in literature that have determined the negative impact on soils due to irrigation of edible crops with greywater, [Qishlaqi et al., 2008]. Pinto et al. [U. Pinto, 2010] discovered that electric conductivity and soil pH were significantly elevated due to greywater irrigation compared to irrigation with other sources. Despite these reports on the accumulation of heavy metals and elevation of pH and EC in long periods of time, overall there were no negative effects on soils due to greywater irrigation in the short term [Faruqui and Al-Jayyousi, 2002] [U. Pinto, 2010].

4.2.1 Macronutrients and Micronutrients in Soil

To understand the effects of greywater irrigation on the quality of soil, a study was conducted to determine the concentration of both macronutrients and micronutrients in the soil [Rodda et al., 2011].

4.2.1.1 Macronutrients

There were no significant differences between the levels of total N, total S, P, Ca, K and Mg concentrations in soil irrigated with nutrient solution and in greywater irrigated soil, but concentrations in soil irrigated with tap water were significantly lower. A trend of increasing concentration with successive crop cycles was noticed for S, P and K [Rodda et al., 2011].

4.2.1.2 Micronutrients

For the other micronutrients such as Zn, Mn and Cu, the concentrations were higher in soils irrigated with greywater. Concentrations in soils irrigated with nutrient solution were intermediate between those in greywater irrigated soil and those in soil irrigated with tap water. No result is reported for Na because of sample loss during analysis [Rodda et al., 2011].

4.2.1.3 Electrical Conductivity

Electrical conductivity of soil irrigated with nutrient solution increased threefold over five crop cycles, while that in greywater irrigated soil increased fourfold. The electrical conductivity remained approximately constant in a low level in soil irrigated with tap water [Rodda et al., 2011].

4.2.2 Heavy Metal Transfer

Since many elements are taken up by plants, irrigation methods are not significantly important concerning heavy metal transfer rates [Rattan et al., 2005]. Zn, Pb and Cu are the more common in greywater [Eriksson et al., 2002]. The main sources of heavy metal contamination are reported to be leaching from pipes and other metal water fixtures [Eriksson et al., 2002]. Therefore, long-term irrigation with greywater can have negative effects on crops and soil [Rattan et al., 2005]. According to Eriksson et al. [Eriksson et al., 2002], these elements can be present in greywater, with maximum values of $1.6 mg/L$ Zn, $0.15 mg/L$ Pb, and 0.39mg/L Cu for greywater of mixed sources.

It has been discussed that plants uptake can reduce the concentration of some heavy metals present in soil. Thus, results of the evaluation of soil irrigated with greywater depend strongly on several environmental conditions and crop type [Mapanda et al., 2005]. The health risk regarding to the consumption of crops irrigated with water containing heavy metals requires more studies with respect to soil conditions and crop species [Finley, 2008].

4.3 Impacts of Greywater irrigation on Human Health

Of all the possible hazards associated with wastewater and greywater reuse, the contamination of crops and soil by pathogen-rich water is known as the most significant threat to human health [Roesner et al., 2007] [Ottosson, 2003] [Christova-Boal et al., 1996]. Yet, the relationship between water and crop contamination is still undetermined. Research carried out by Jackson et al. [Jackson et al., 2006] reported there was no significant difference in bacterial levels on plant surfaces which had been irrigated with different water sources: greywater, tap water, or hydroponic solution. This study was performed in a situation where the greywater consisted of high bacterial counts whereas none of the other water sources contained bacterial colonies. Even when edible parts of a crop are not affected, soil contamination can itself be dangerous [Finley, 2008].

Santamaria and Toranzos [Santamaria and Toranzos, 2003] discussed about possible conditions where enteric pathogens spread in the soil. In crop studies, the microbial pollution of soil becomes important when edible parts of crop are in the root, rather than the leaf. Because root crops are much more exposed to the soil, they are more easily contaminated with bacteria-rich irrigation water. For instance, Rosas et al. [Rosas et al., 1987] performed a research and found that up to 94% of the fecal coliforms in wastewater irrigated crops were isolated from the roots of the plant.

4.3.1 Pathogen Transmission by Greywater Irrigation

Plant intake is not the only way to transmit pathogens. The irrigation method should be considered in the reuse of greywater. The study conducted by Finley [Finley, 2008] suggests that direct transmission of pathogenic microorganisms from greywater to plant surface is the most important factor in health risk [Gerba and Smith, 2005]. In order to avoid the direct transmission of pathogens, it is recommended to install subsurface irrigation networks, which deliver water a few centimeters beneath the surface of the soil. The proposed scheme distributes greywater with no direct contact with plant surfaces. Sadovski et al. [Sadovski et al., 1978] showed that burying irrigation pipes can reduce pathogen levels on crop surfaces to undetectable levels. Armon et al. [Armon et al., 1994] compared two schemes of irrigation to evaluate the transmission of protozoan cysts onto zucchini surfaces: spray irrigation and subsurface irrigation. Evaluation showed that spray irrigation led to higher transmission of studied protozoan cysts.

4.4 Conclusion

To evaluate the effects of irrigation with greywater on plants, it is required to study three different aspects.

It can be concluded that greywater can accelerate plant growth. Plants such as cotton lint and barley grew faster in the experiments because of the increase in N, P, and K in the soil. However, in situations where greywater increased the concentration of Na, plants such as pepper, tomato and corn showed a reverse trend. It should be noted that most of the crops are sensitive to the increase of Na concentration in the soil. Besides, the increase of Na in the soil can affect the soil health negatively. The increase of EC that follows the increase of Na in soil can also impact the soild health. Therefore, in situations when greywater contains dissolved salt, cautions should be considered.

Evaluation of greywater irrigation on the crop quality and crop yield shows a similar trend. There are some plants that are positively affected when irrigated with greywater. Cotton yield showed a positive response to greywater due to the presence of micronutrients. Tomato showed different trends in different experiments. In Jordan, it was reported that tomato yield was not improved as the result of greywater irrigation, however tomato yield being irrigated with greywater in Ghana improved significantly. It can be concluded that the contents of greywater play an important role in crop yield. Regarding the negative impacts of the greywater irrigation on crop yield, no decrease has been reported in the previous studies.

Regarding crop quality, longtime irrigation with greywater increased the lettuce uptake of heavy metals, which may affect the quality of the leaves. But potato showed no increase in yield when irrigated with greywater compared to tap water irrigation.

Concerns on the human health should be directed toward the heavy metals uptake. It has been shown that plants like lettuce accumulate more Cd and Pb when they are irrigated with greywater for long time (10 years or more). That is because of the increase in the heavy metals in the soil contents. Besides, there are some concerns regarding the transmission of pathogens due to the presence of fecal coliform in the greywater; however, it should be mentioned that the fecal coliform presence in greywater is less than in wastewater. It means that obeying same cautions for greywater irrigation can reduce the risk of pathogen transmission.

Chapter 5

Conclusion

The objective of the current thesis was to study the effects of greywater irrigation on the quality of crops. Besides, it tried to provide a comprehensive study of the effects of greywater on the quality of soil by studying different researches.

Considering the fertility of soil and the studied researches, it can be concluded that fertilizer should be applied to crop fields to supply the nutrients which are not present in greywater, to enable optimal growth of the plants.

In the previous chapters, it has been shown that greywater has been analyzed to be used for many irrigation purposes. Comparing with tap water, the nutrients and minerals (including both macro and micro), have been proved to affect the plants.

Not only the type of water being used in irrigation, but also the irrigation method can influence not only the content, but also the risk factor of edible parts.

Concerning yield, the results of the studies, showed that the response of leafy, root or bulbous vegetable crops remains unclear. Therefore, the effect of greywater is unclear on leafy or root crops.

In the case of aesthetic evaluation of crop appearance, the studies reported negative impacts of greywater irrigation on some crops. Spinach, carrots and lettuce were negatively affected due to greywater irrigation, but cabbages, onions and beetroot presented only minimal effects.

Different studies revealed that irrigation water quality can be manipulated to obtain the desired crop quality.

Regarding the concerns about the health risk of consumers due to the effects of greywater on irrigation of crops, special attention should be considered.

5.1 Recommendations for Greywater Irrigation

The use of household products containing minimal boron contents is recommended [Ng, 2004].

The use of household products containing lower sodium contents, such as liquid detergents instead of powdered cleaners, is recommended [Ng, 2004].

To avoid devastating effects of alkaline chemicals present in greywater, care must be taken when using greywater to irrigate plants preferring shade and acid soils, such as azaleas, camellias, gardenias, begonias, and ferns [Prillwitz and Farwell, 1995]. The pH levels of irrigated soils may be managed by adding soil conditioners [Ng, 2004].

Greywater irrigation increased soil EC, indicating that it could lead to soil salinity and sodicity in time. Therefore, mixing domestic greywater with freshwater and low-grade fertilizer can be used for small scale irrigation to prevent the accumulation of Na and metals in soils and in plants. This is especially important for root crops, and in areas with low rainfall during the growing season, since the mitigating effect of rain would then be minimal. Results reported here are valid for below-ground application of greywater only [Rodda et al., 2011].

5.2 Health Safety Recommendations

5.2.1 Irrigation Method on Pathogen Transmission

In order to avoid the direct transmission of pathogens, it is highly recommended to install subsurface irrigation networks, which deliver water a few centimeters beneath the surface of the soil. The proposed scheme provides greywater without any direct contact with plant surfaces [Sadovski et al., 1978] [Armon et al., 1994] [Finley, 2008].

Great care should be taken regarding the use of greywater for edible crops, which may provide hazards for human health [Ng, 2004]. Nevertheless, if recommendations are taken into consideration, almost all studies have proved that greywater reuse for irrigation is not a source of human health hazard. The only possible real health hazard from the greywater systems studied is possible contact with the contaminants in the storage tank. Therefore, it is important to make appropriate precautions during regular maintenance events [Ng, 2004].

5.3 Recommendations for Future Studies

Since there have been few studies on the effects of greywater on crops irrigation, there are some recommendations for future studies:

- It is recommended to carry out studies to identify the fertilizer regime required by the irrigated crops, and the long-term impacts of primary treated greywater reuse on the irrigated soils and plants.
- Another recommendation is to examine the greywater reuse system to identify possible optimizations in the system's performance and cost. Studies that compare, contrast, and encompass issues relating to the various available options for reuse would also be beneficial [Ng, 2004].

Finally, the following areas for further investigations were identified through the comparisons of the different investigations made in the thesis:

- It is necessary to study the marketability of crops irrigated with greywater.
- Studies should be carried out about the social acceptance of irrigating crops with greywater.
- Further research on greywater dilution rates will be useful to measure an appropriate ratio of greywater to potable water in order to elevate the quality of irrigation water.
- A study should be performed to investigate the reasons why irrigating with greywater increases crop yield but reduces crops aesthetic appeal and chemical quality.

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